US010269458B2

(12) **United States Patent**
Wong

(10) **Patent No.: US 10,269,458 B2**
(45) **Date of Patent: Apr. 23, 2019**

(54) **REACTOR USING ELECTRICAL AND MAGNETIC FIELDS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **15/589,913**

(22) Filed: **May 8, 2017**

(65) **Prior Publication Data**

US 2017/0337989 A1 Nov. 23, 2017

Related U.S. Application Data

(63) Continuation-in-part of application No. 14/318,246, filed on Jun. 27, 2014, now abandoned, which is a continuation-in-part of application No. 14/205,339, filed on Mar. 11, 2014, now Pat. No. 9,245,654, which is a continuation-in-part of application No. 12/850,633, filed on Aug. 5, 2010, now abandoned.

(60) Provisional application No. 61/925,142, filed on Jan. 8, 2014, provisional application No. 61/925,131, filed on Jan. 8, 2014, provisional application No.
(Continued)

(51) **Int. Cl.**

H05H 1/02	(2006.01)
G21B 1/05	(2006.01)
G21B 3/00	(2006.01)

(52) **U.S. Cl.**

CPC ***G21B 1/05*** (2013.01); ***G21B 3/006*** (2013.01); *Y02E 30/126* (2013.01)

(58) **Field of Classification Search**

CPC . G21B 1/00; G21B 1/05; G21B 1/055; G21B 1/057; G21B 1/11; G21B 1/15; G21B 1/21

USPC 376/100, 121, 123, 124, 130, 142, 143, 376/144, 150, 151, 152

See application file for complete search history.

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(Continued)

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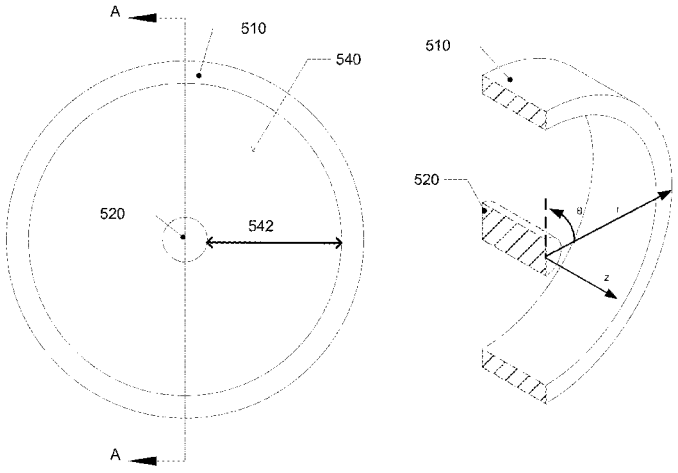
(57) **ABSTRACT**

Methods, apparatuses, devices, and systems for producing and controlling and fusion activities of nuclei. Hydrogen atoms or other neutral species (neutrals) are induced to rotational motion in a confinement region as a result of ion-neutral coupling, in which ions are driven by electric and magnetic fields. The controlled fusion activities cover a spectrum of reactions including aneutronic reactions such as proton-boron-11 fusion reactions.

18 Claims, 30 Drawing Sheets



Related U.S. Application Data

61/925,114, filed on Jan. 8, 2014, provisional application No. 61/925,122, filed on Jan. 8, 2014, provisional application No. 61/925,148, filed on Jan. 8, 2014, provisional application No. 61/843,015, filed on Jul. 4, 2013, provisional application No. 61/841,834, filed on Jul. 1, 2013, provisional application No. 61/840,428, filed on Jun. 27, 2013, provisional application No. 61/776,592, filed on Mar. 11, 2013.

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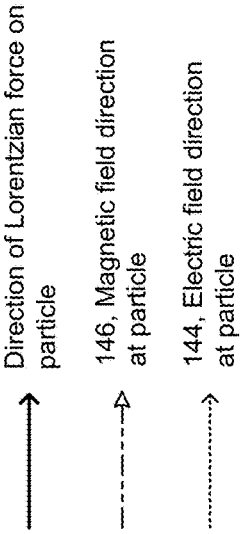
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144, Electric field direction at particle

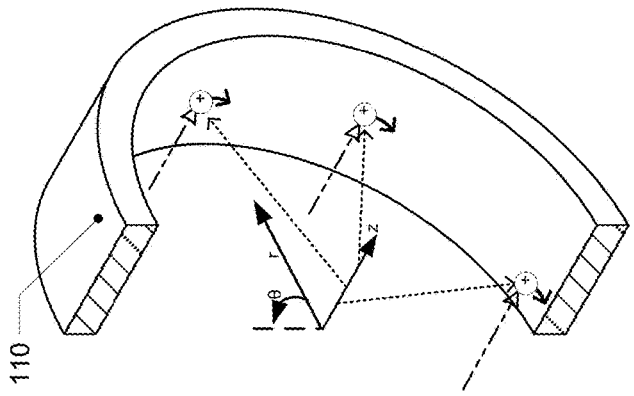


FIGURE 1c

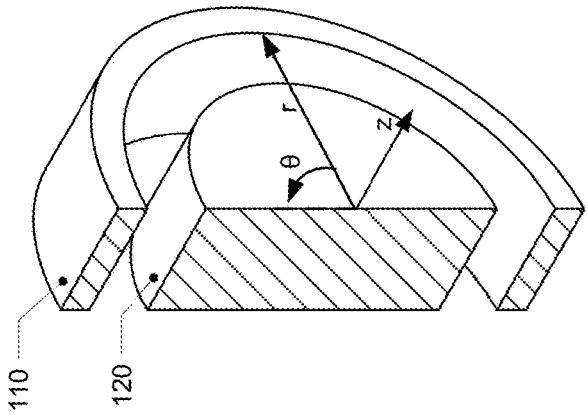
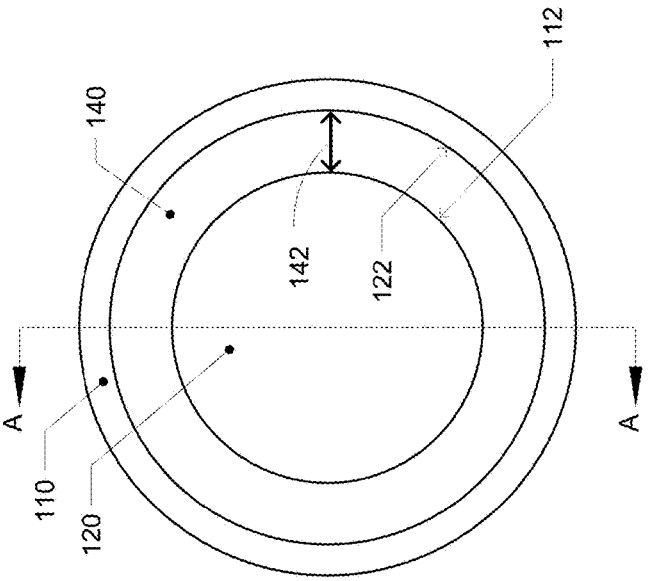


FIGURE 1b



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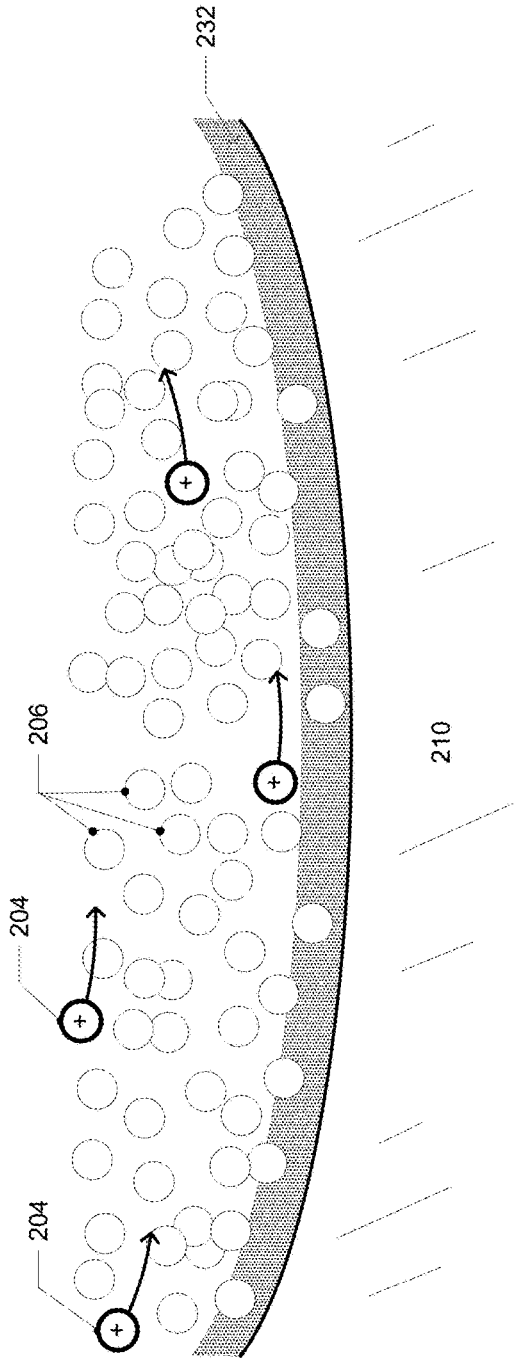

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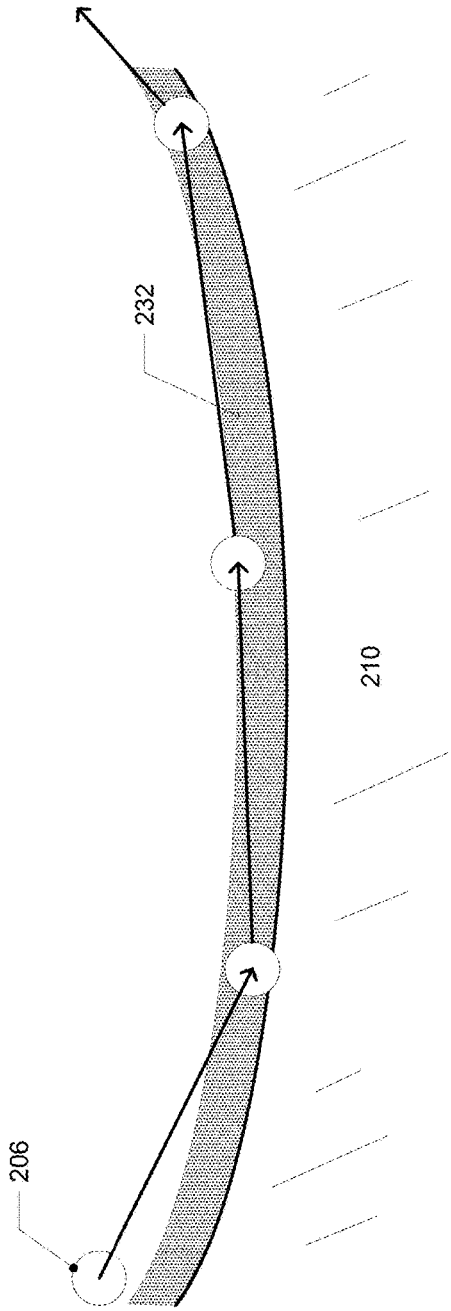

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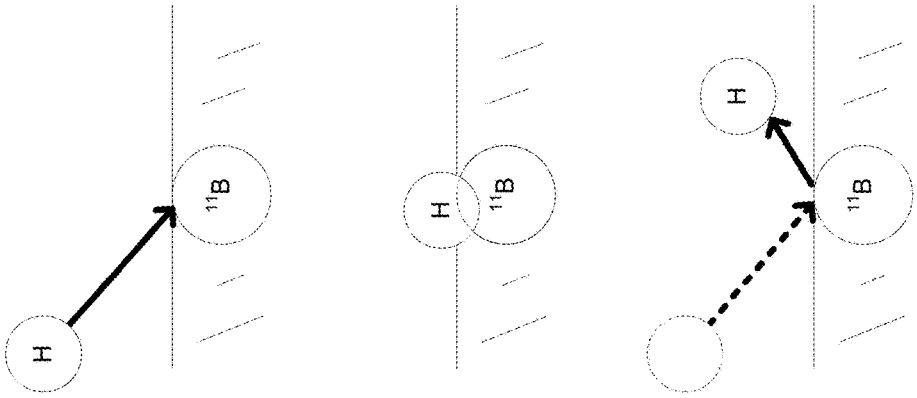


FIGURE 3b

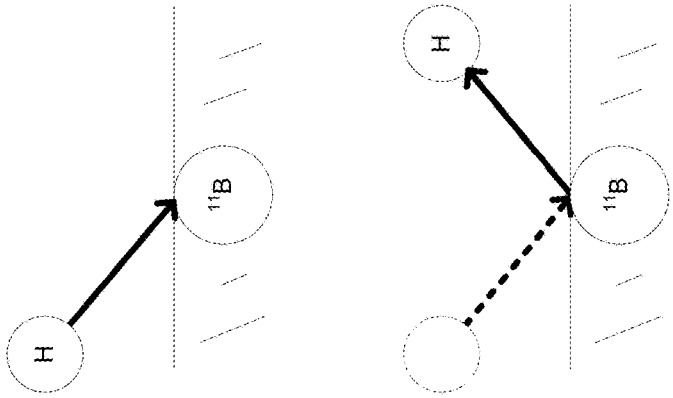
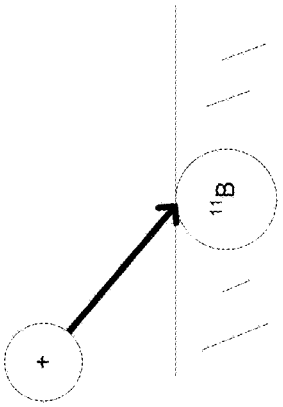


FIGURE 3a



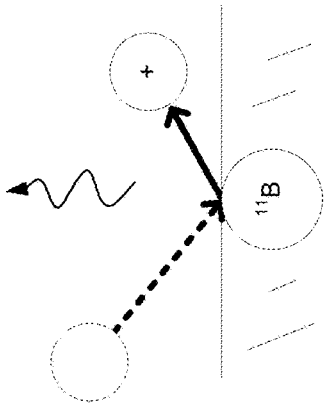
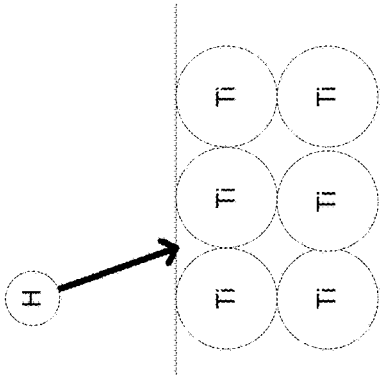


FIGURE 3d



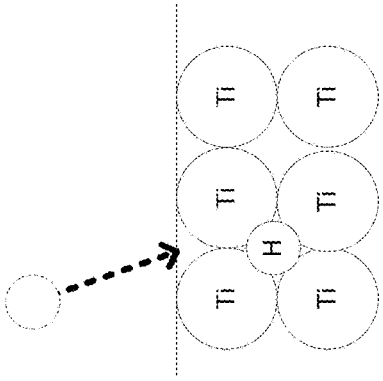
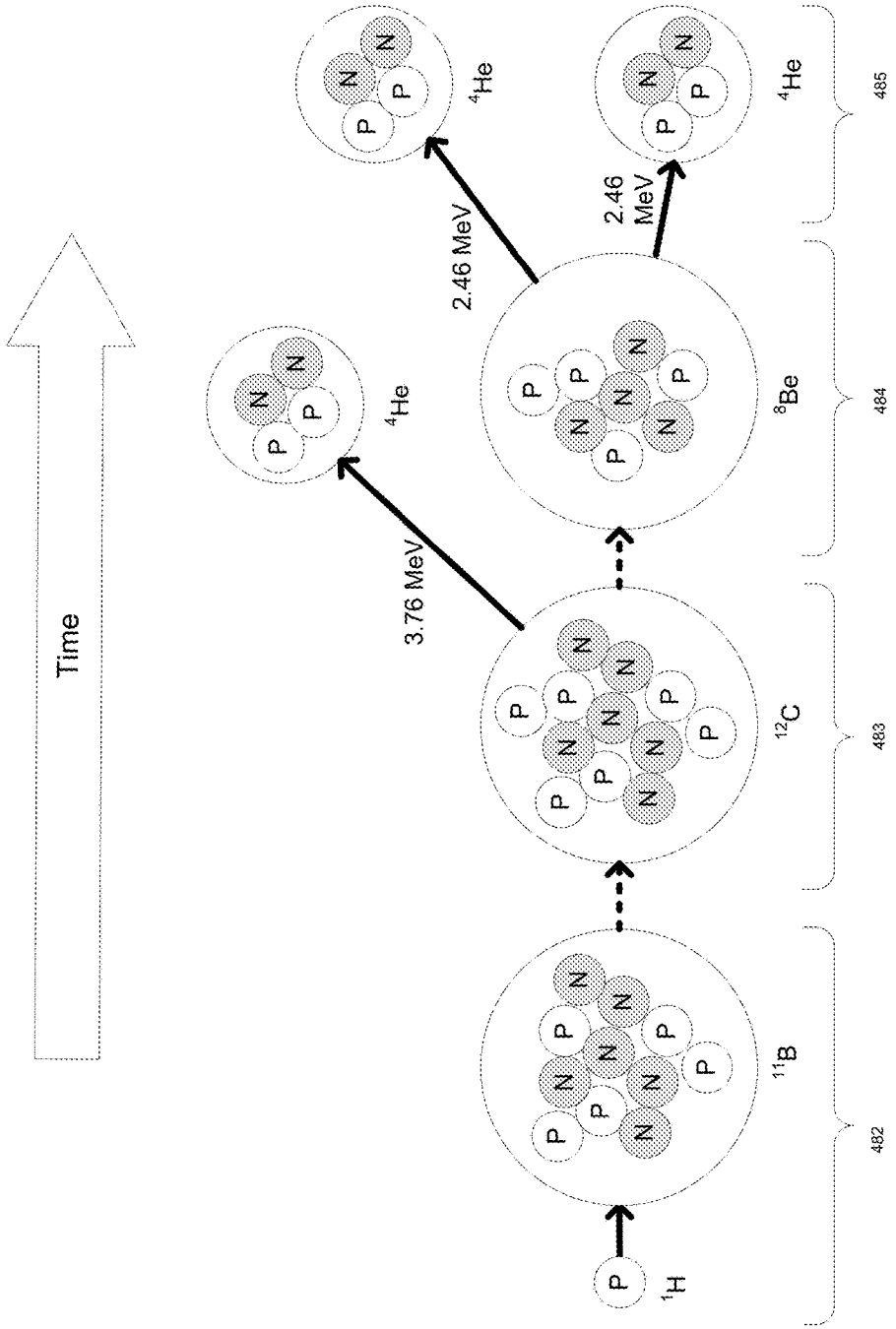


FIGURE 3c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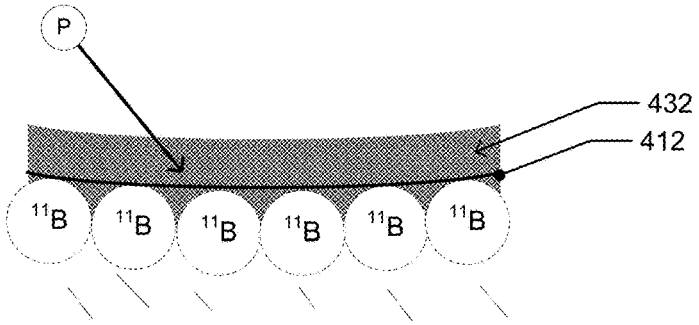
484
485

FIGURE 4a



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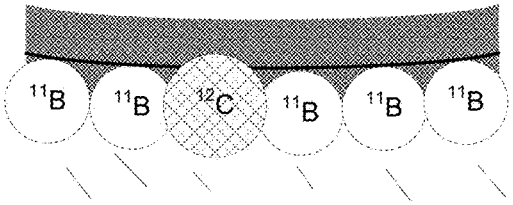

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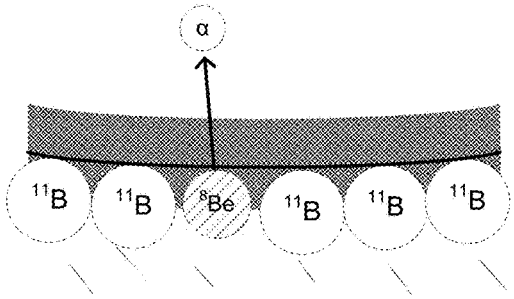


FIGURE 4d

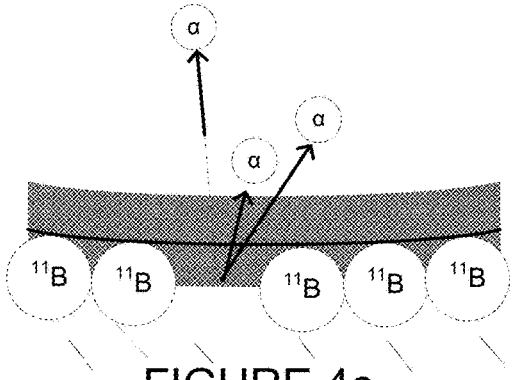


FIGURE 4e

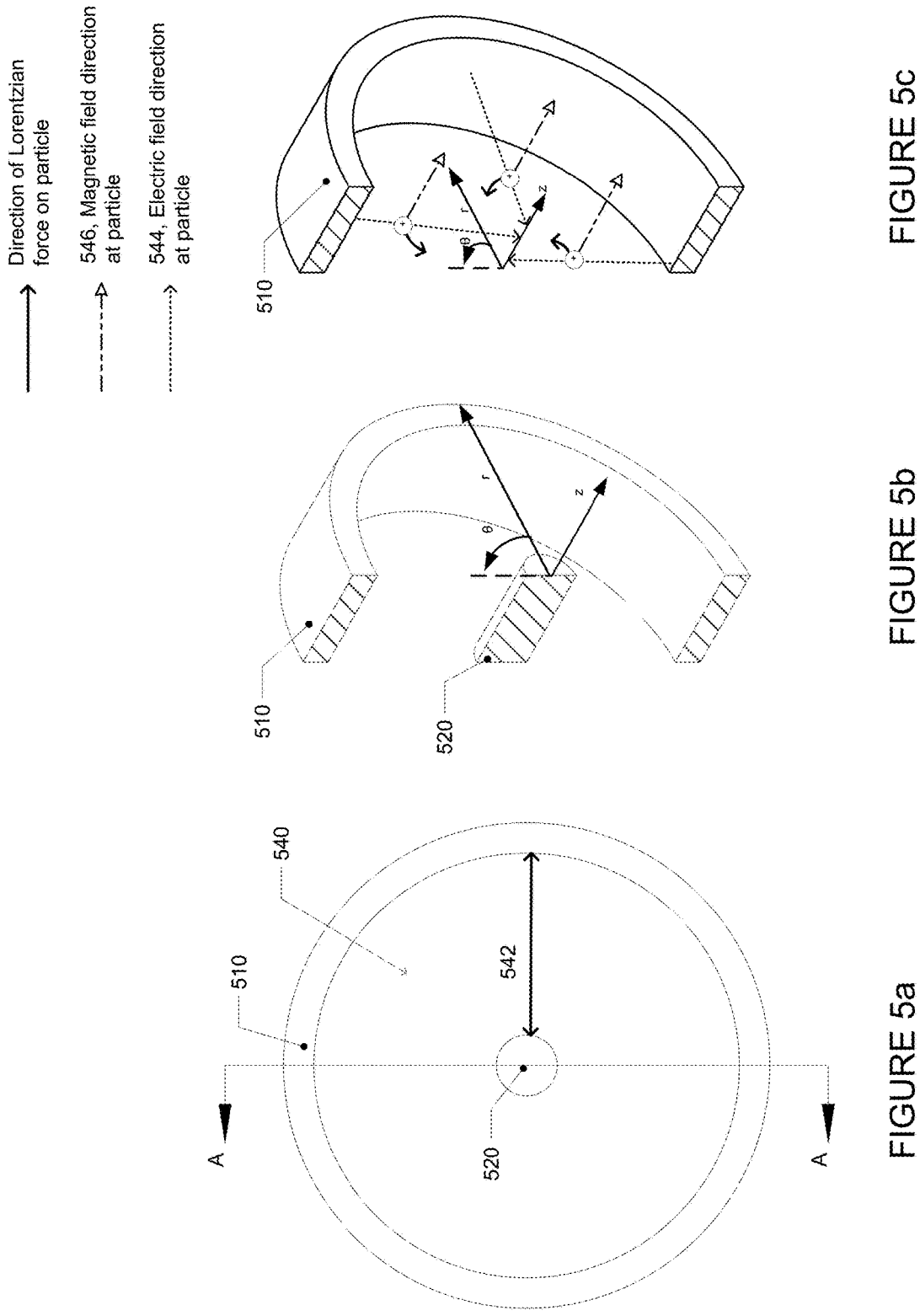
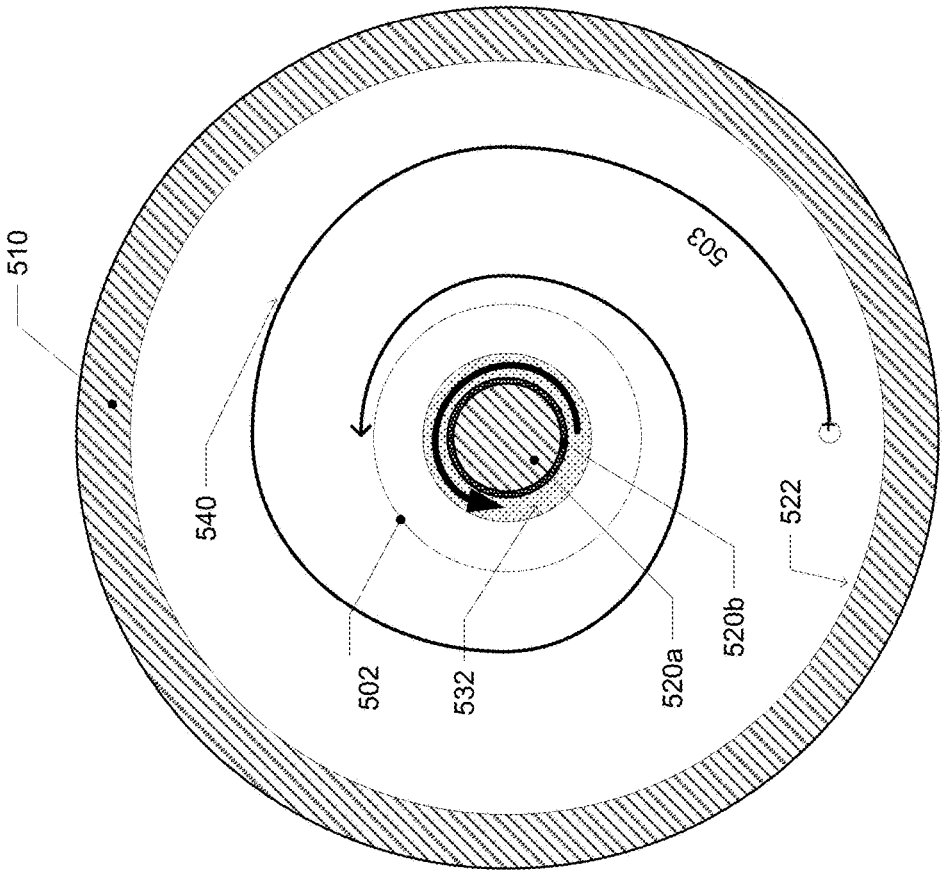


FIGURE 5c

FIGURE 5b

FIGURE 5a



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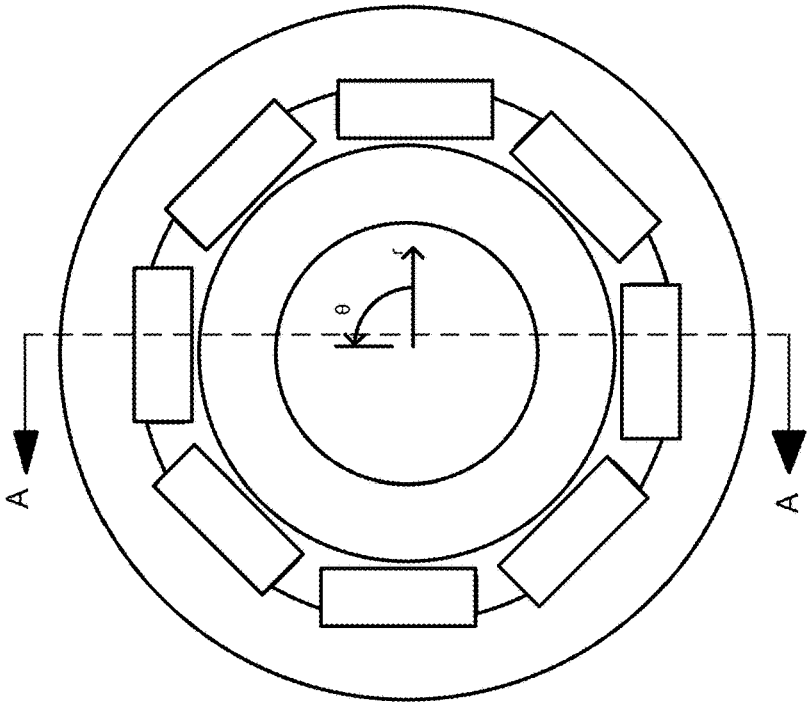

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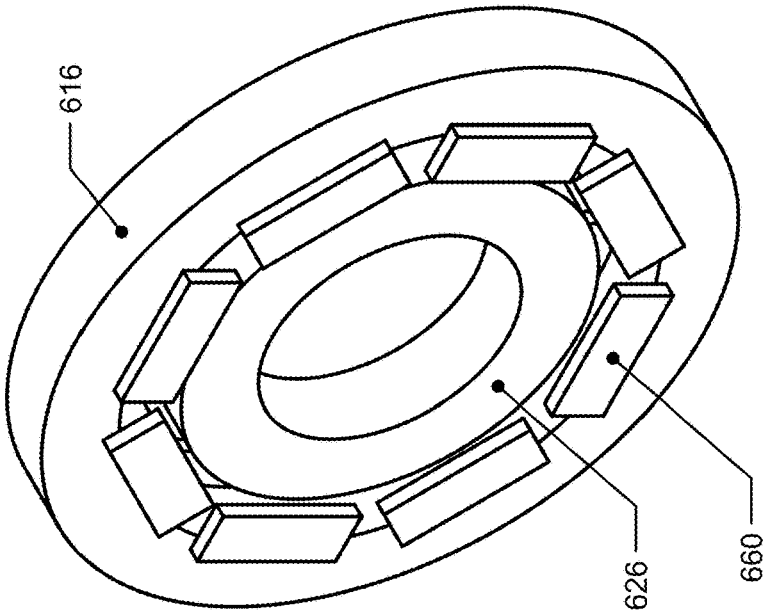

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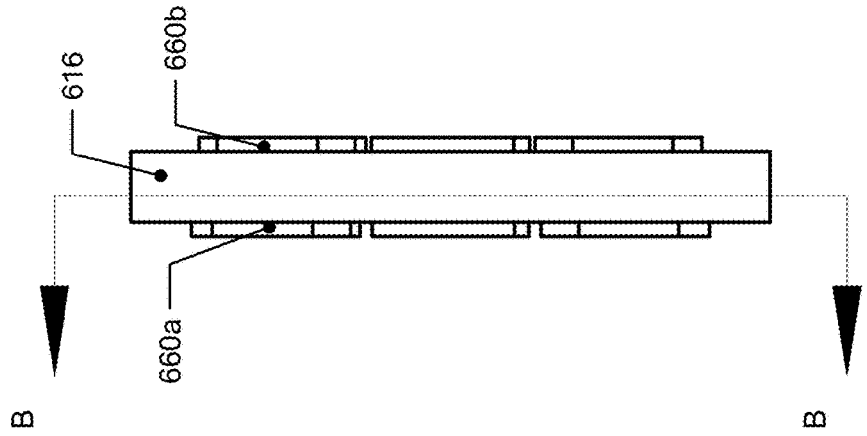

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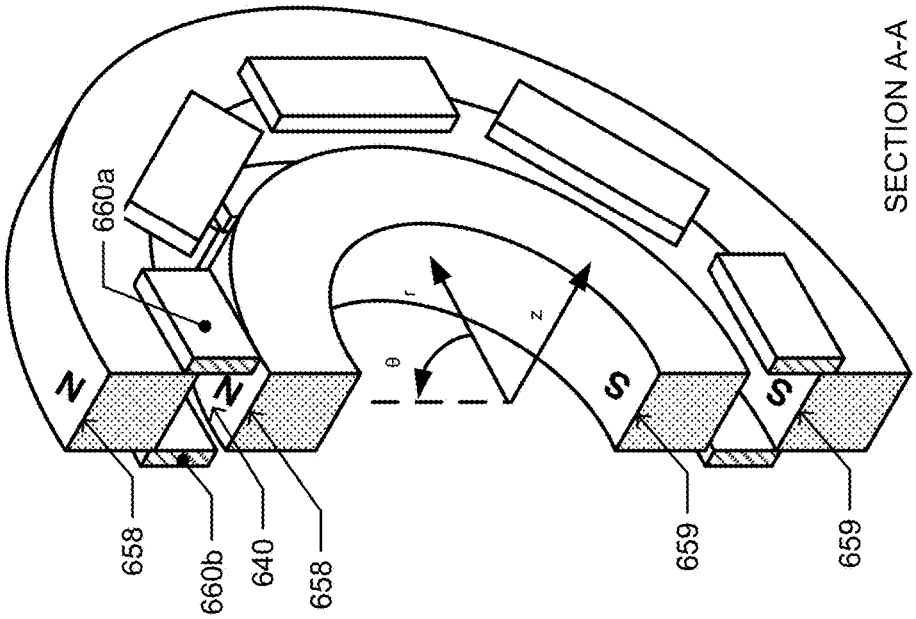
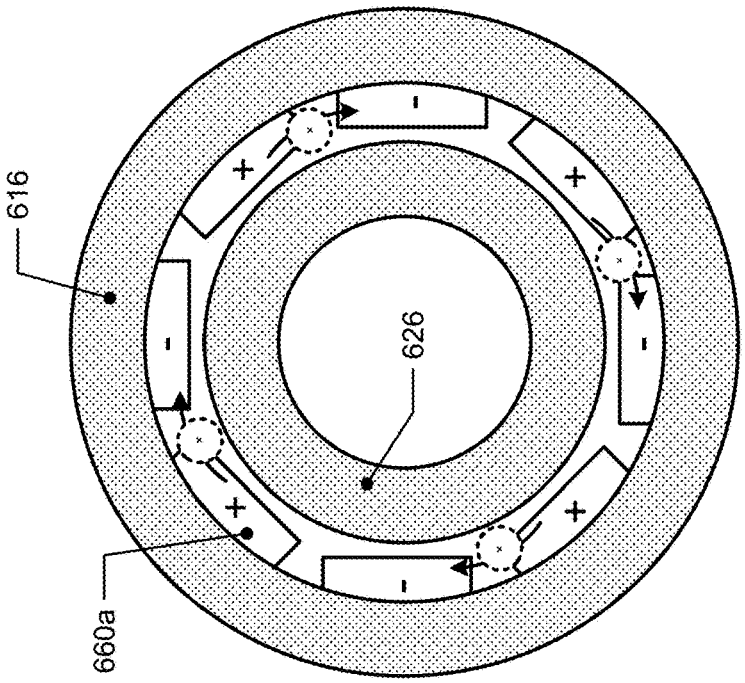


FIGURE 6c



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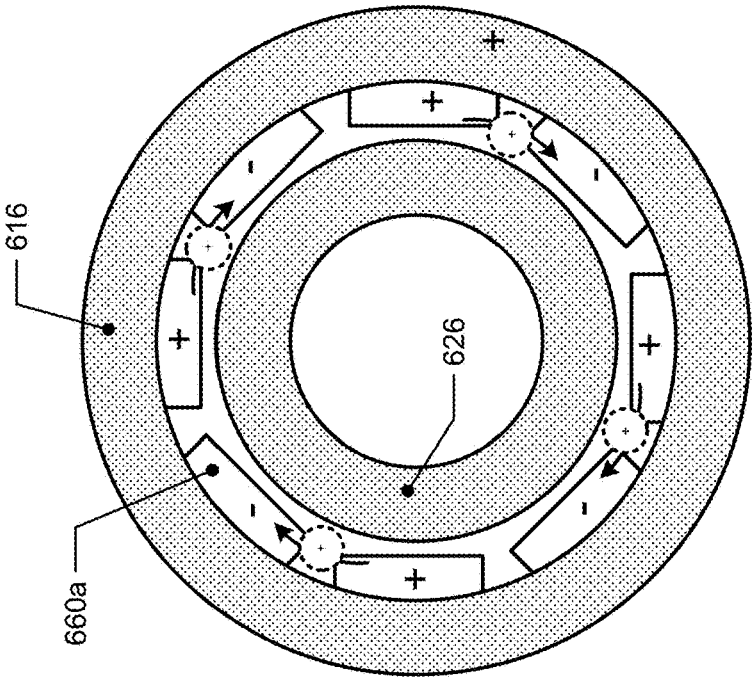

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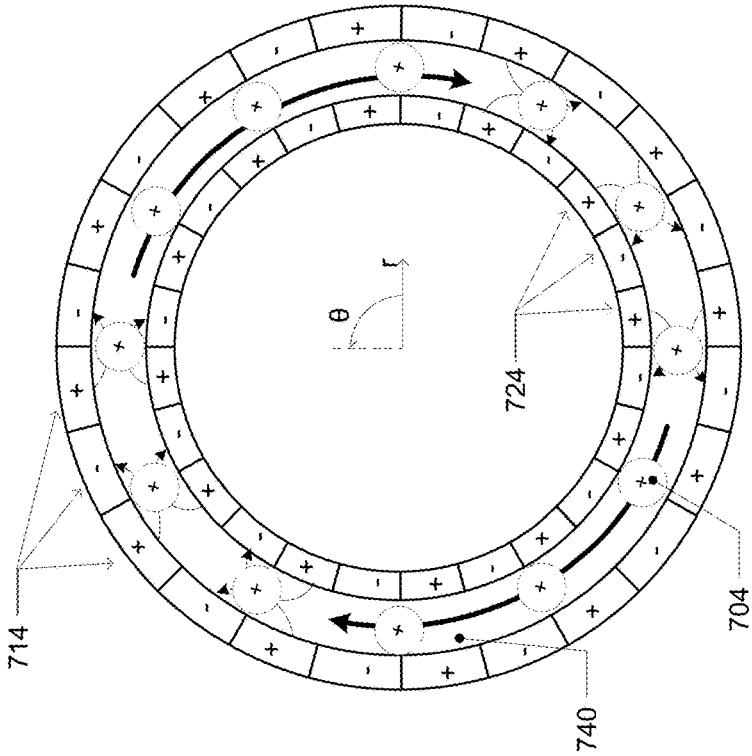
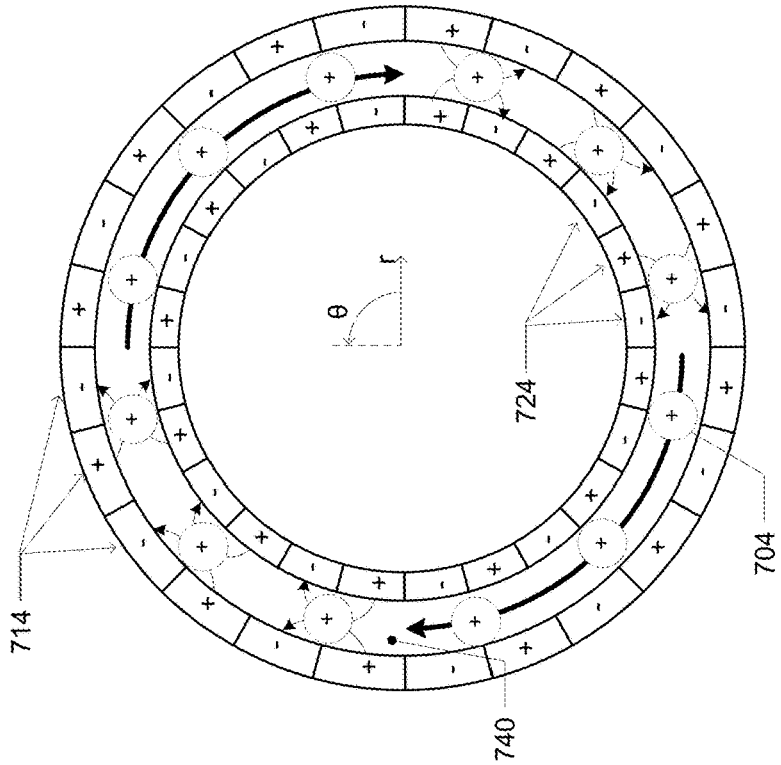


FIGURE 7b



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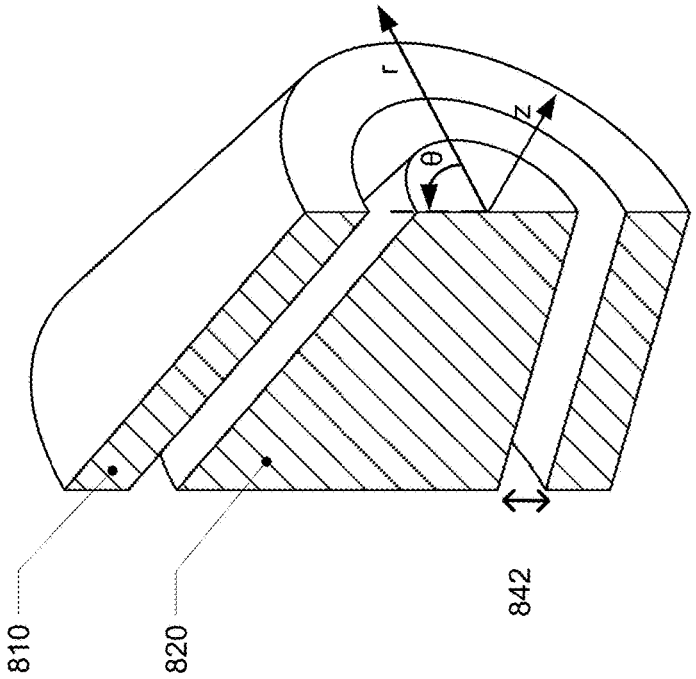

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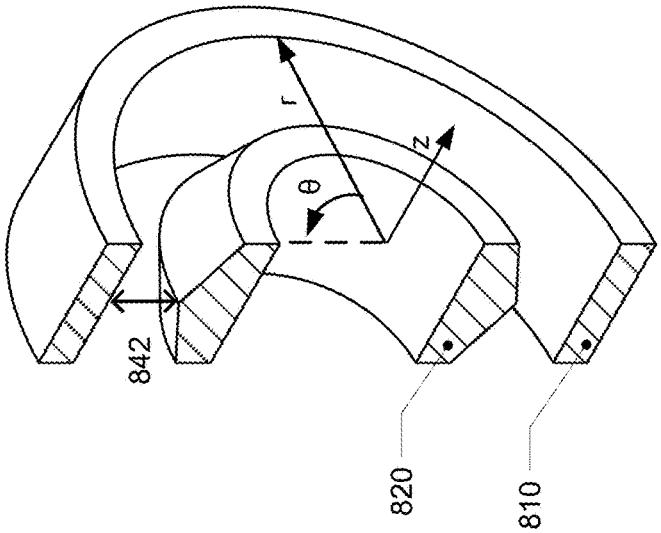

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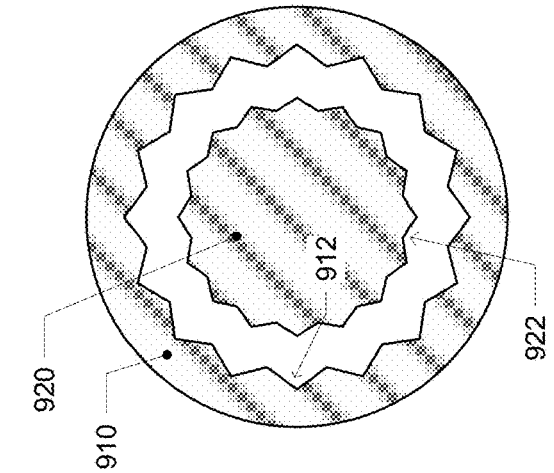
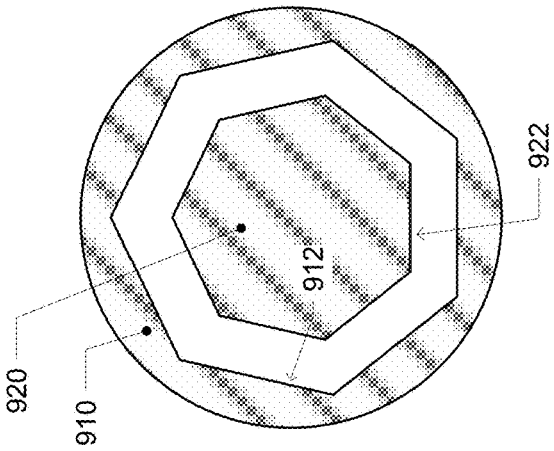


FIGURE 9c



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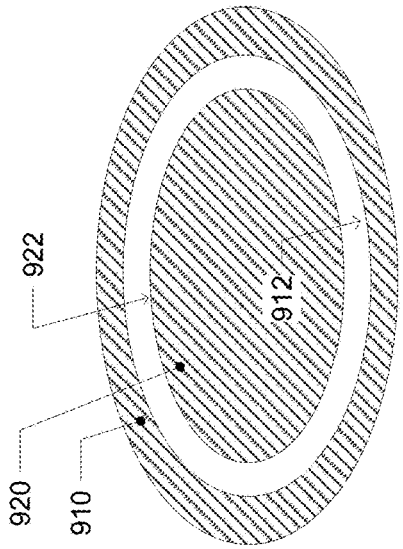

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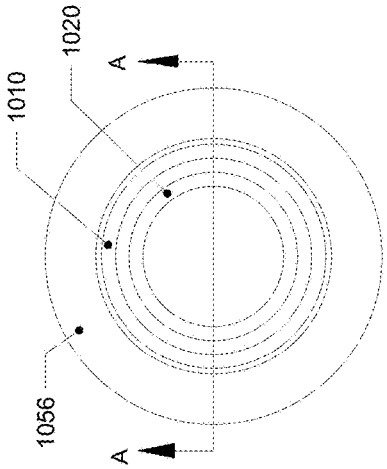

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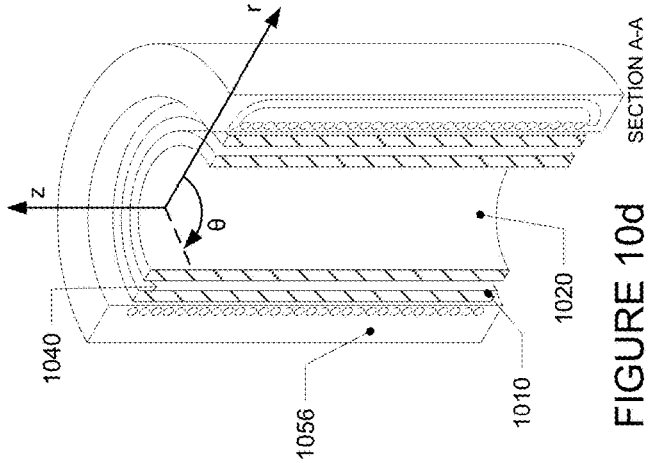

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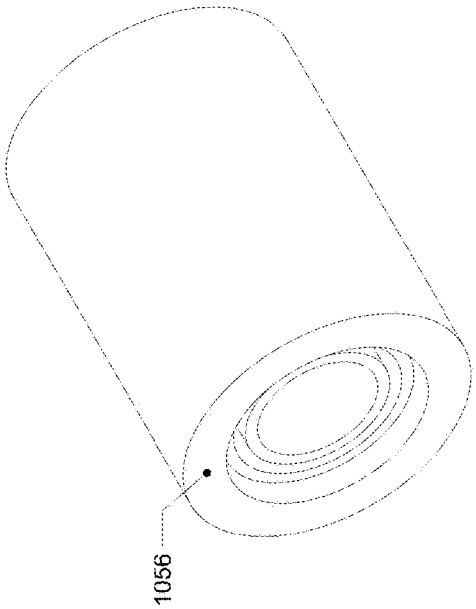

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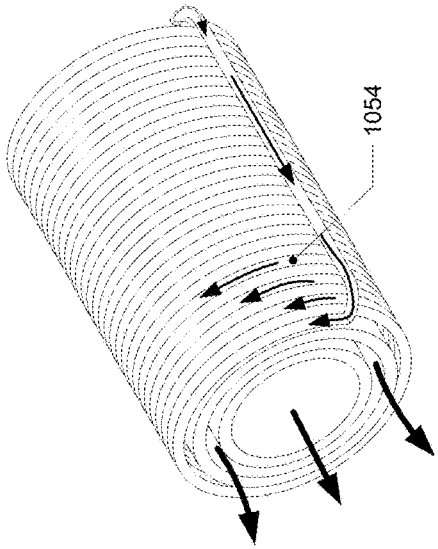

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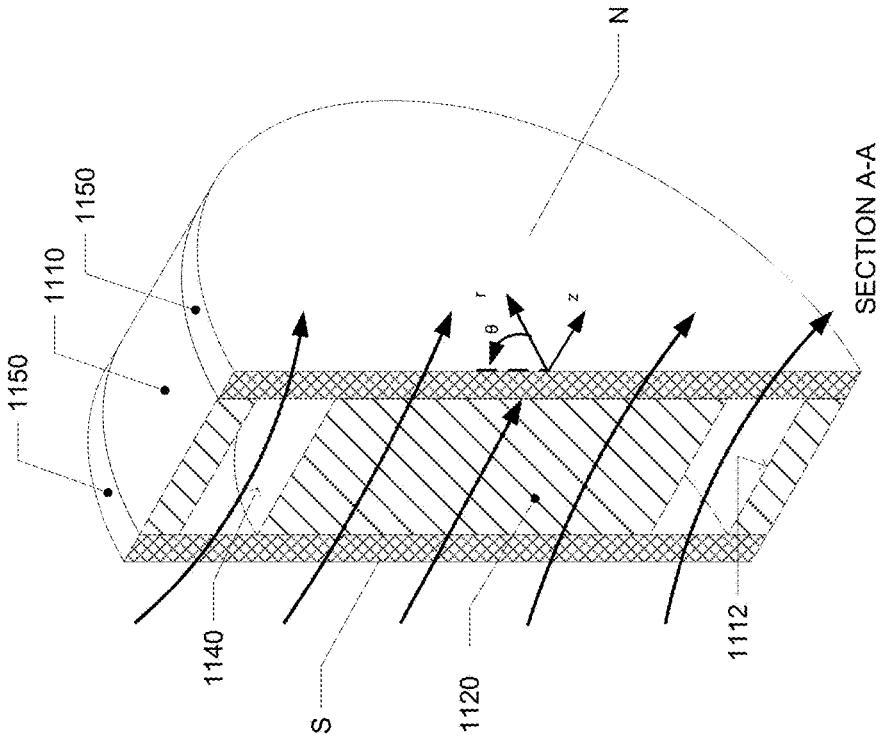

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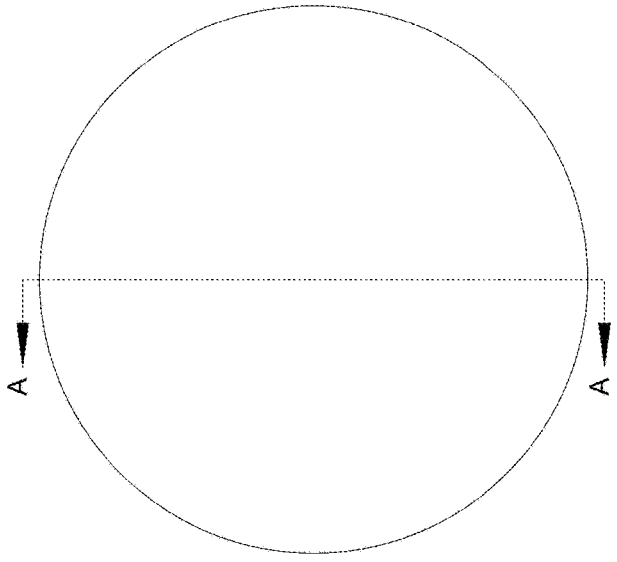

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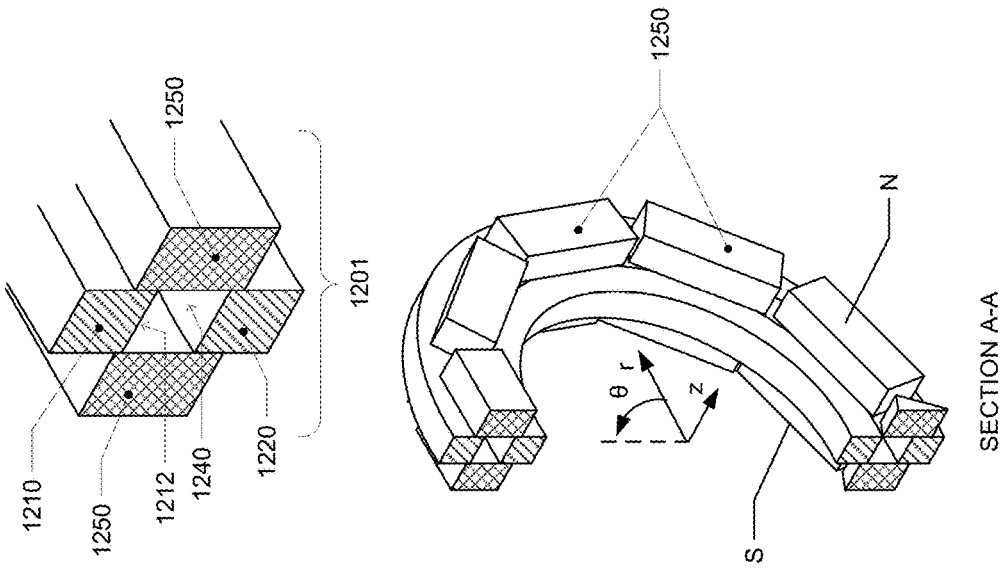

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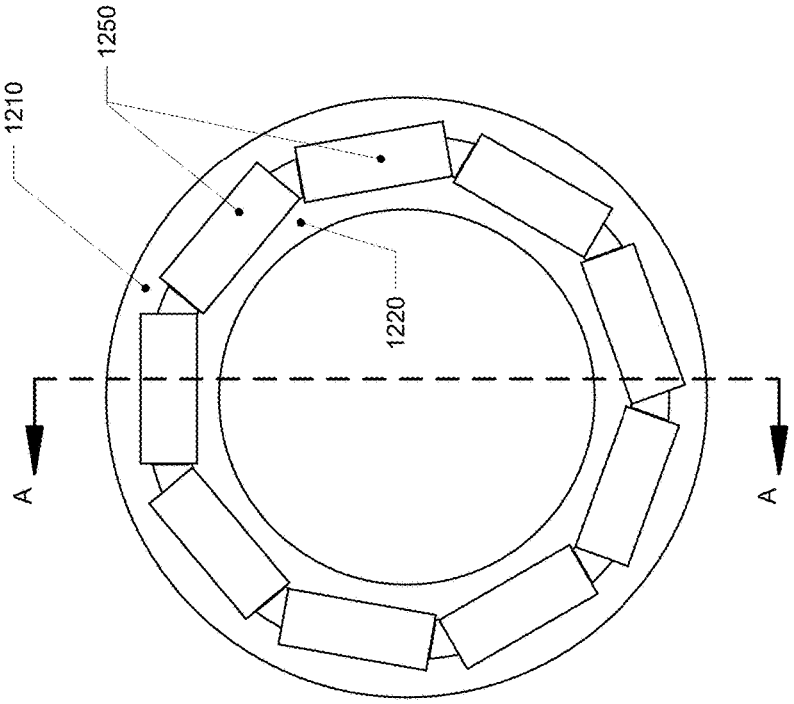

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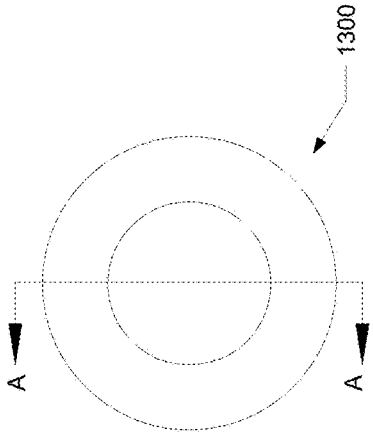

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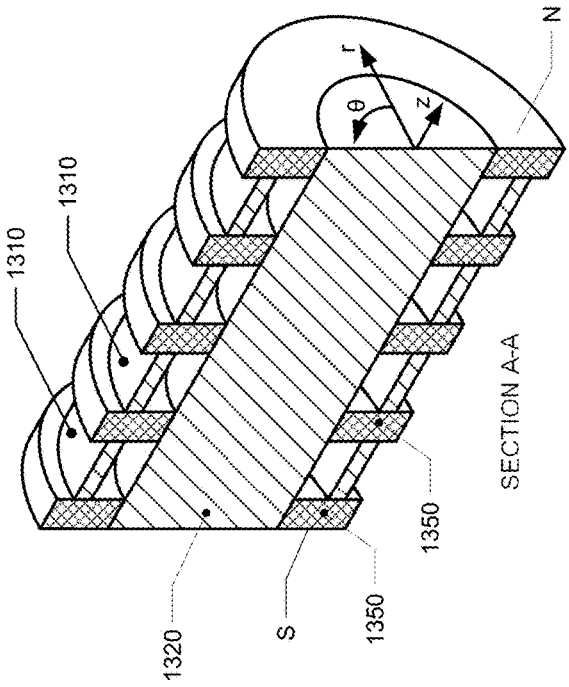
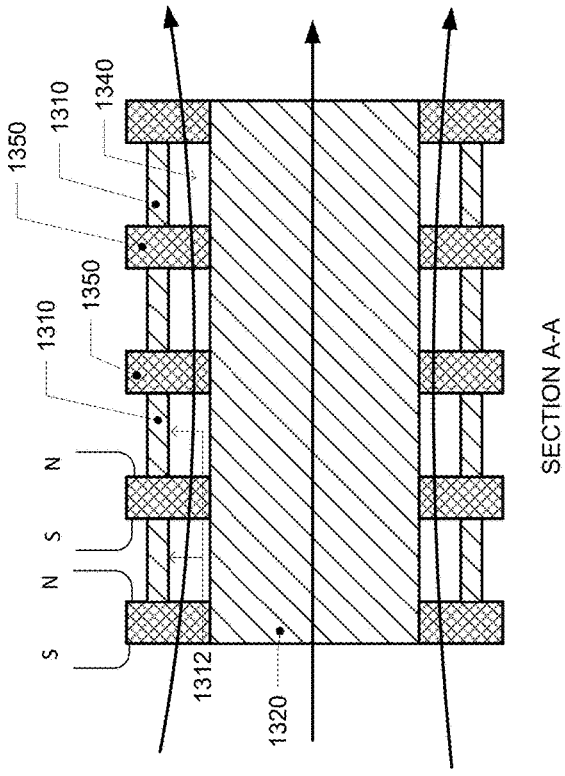


FIGURE 13c



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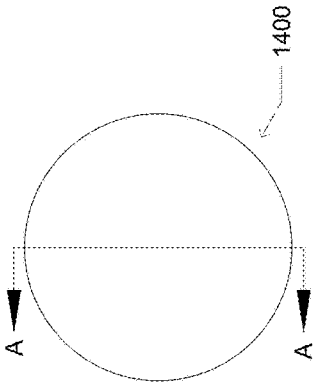

FIGURE 14a

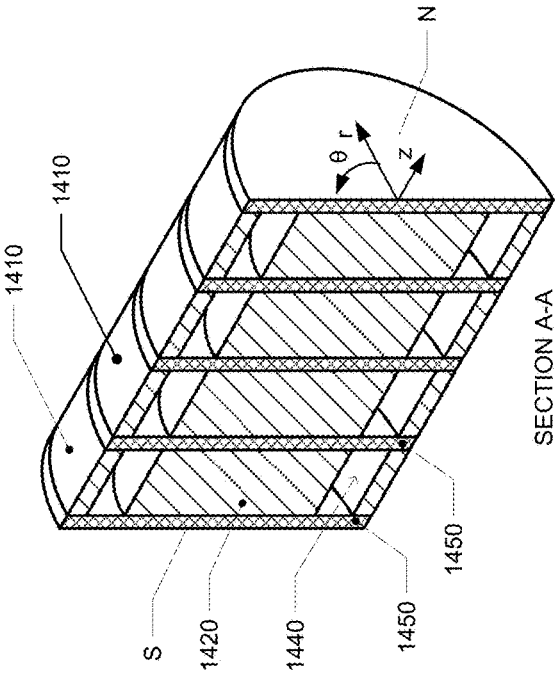

FIGURE 14c

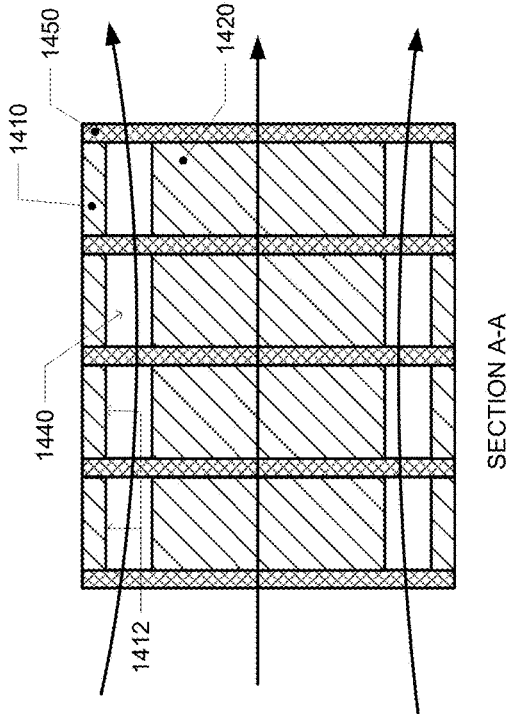

FIGURE 14b

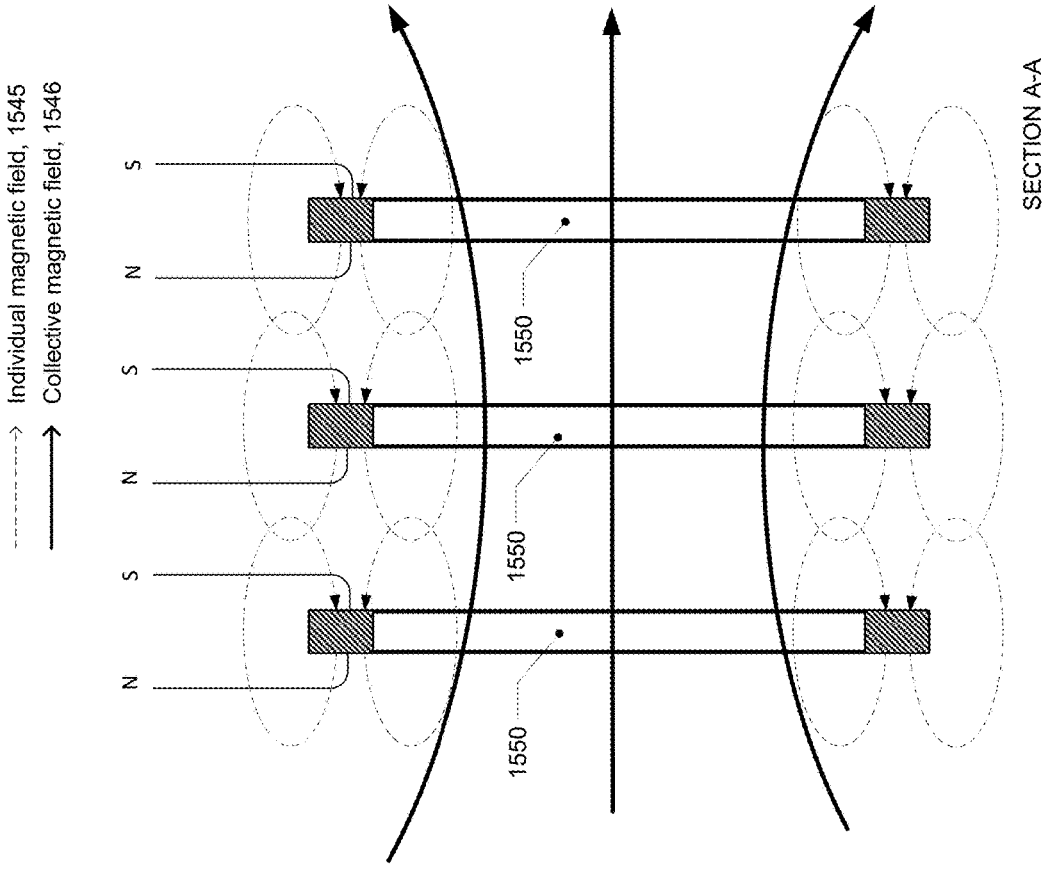

FIGURE 15c

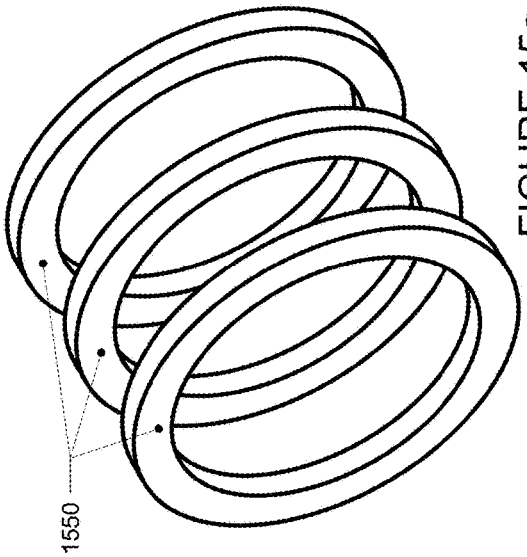

FIGURE 15a

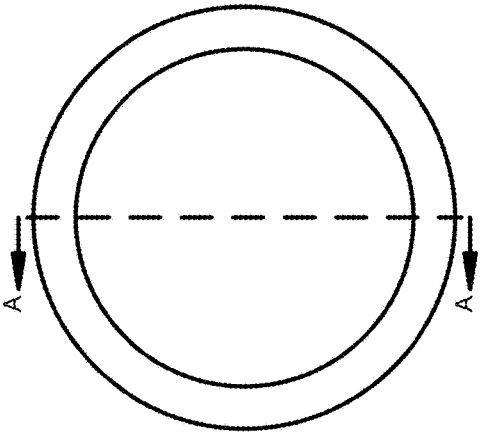

FIGURE 15b

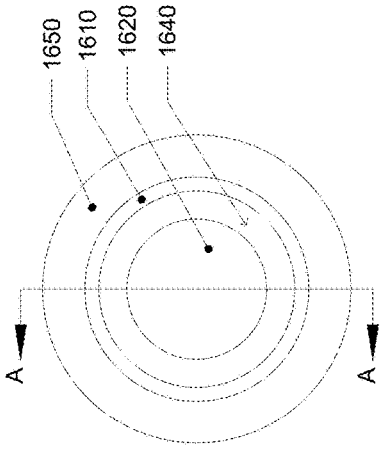

FIGURE 16a

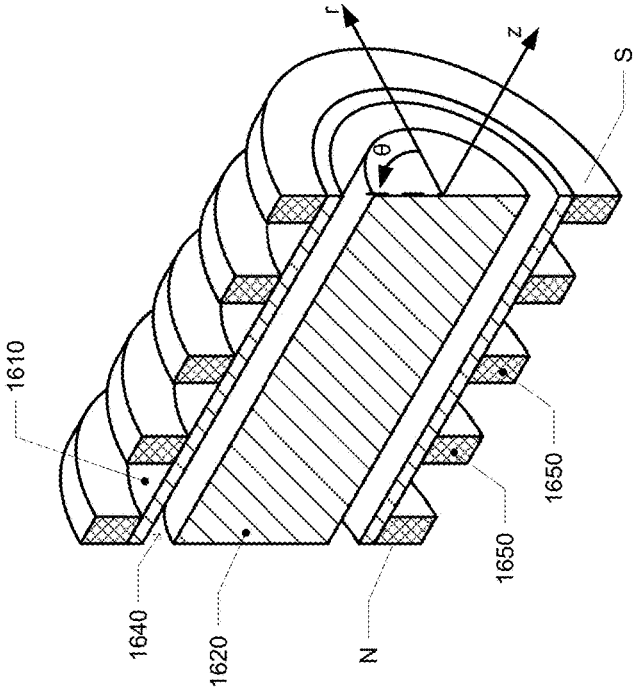

FIGURE 16c

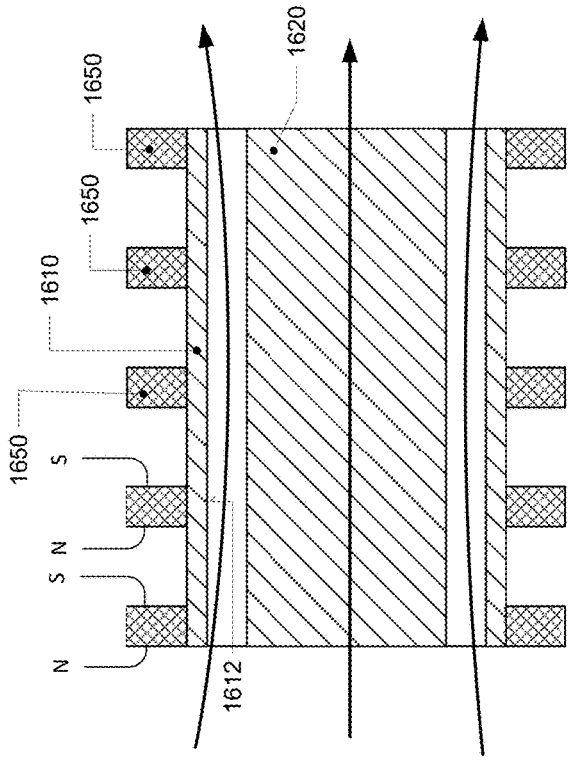

FIGURE 16b

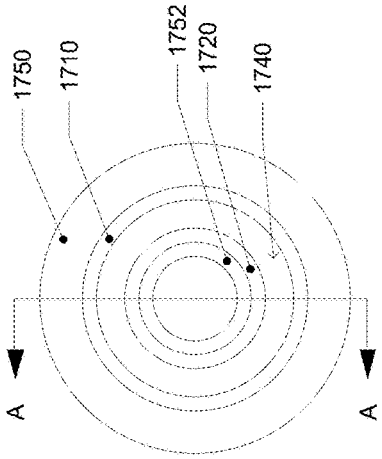

FIGURE 17a

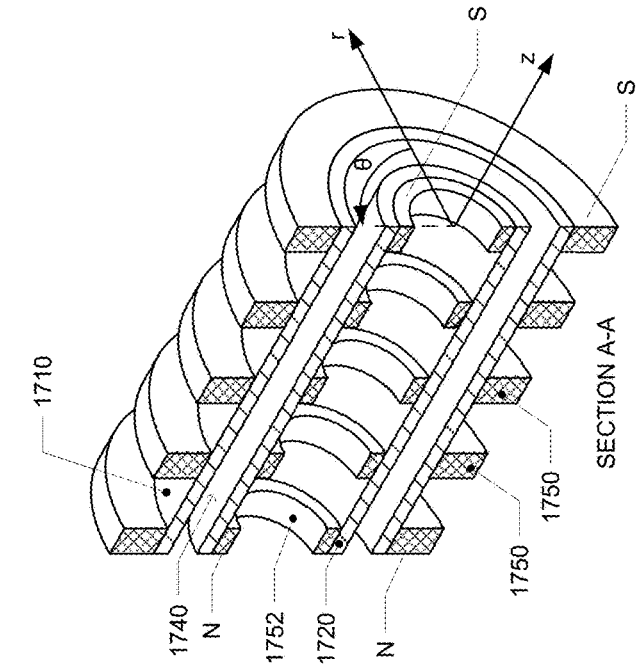

FIGURE 17c

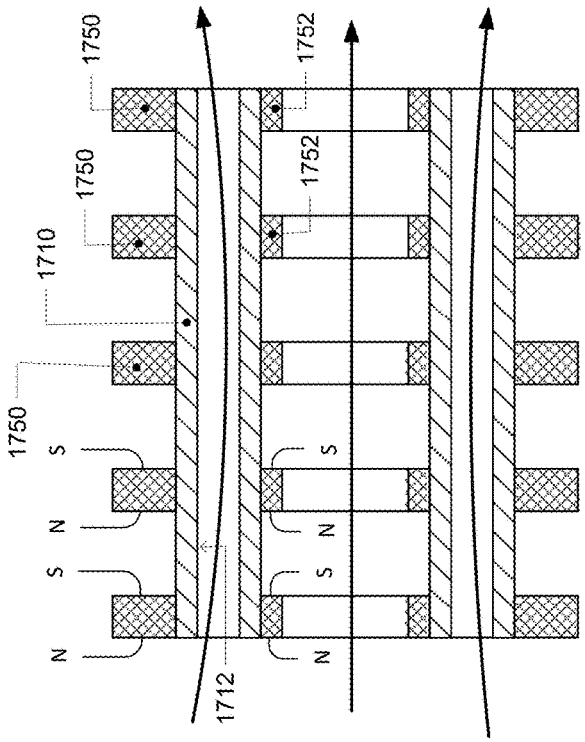

FIGURE 17b

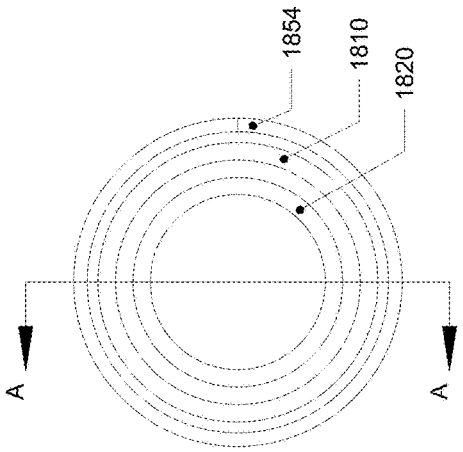

FIGURE 18b

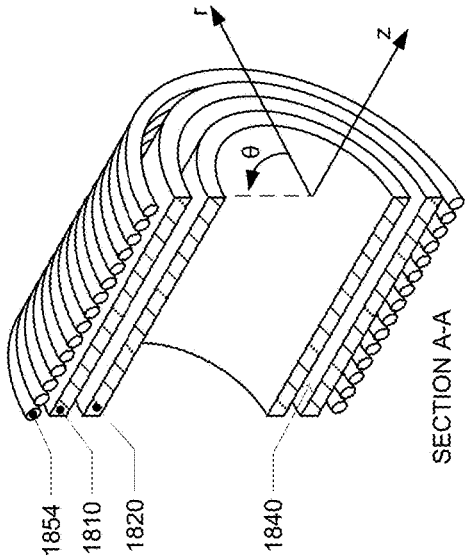

FIGURE 18d

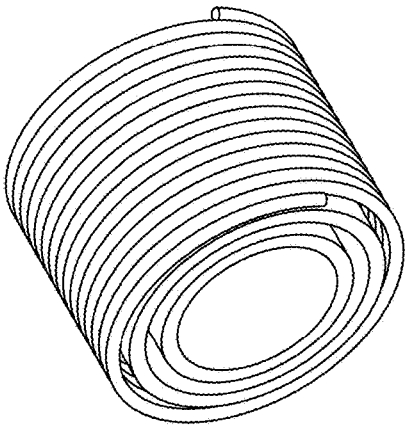

FIGURE 18a

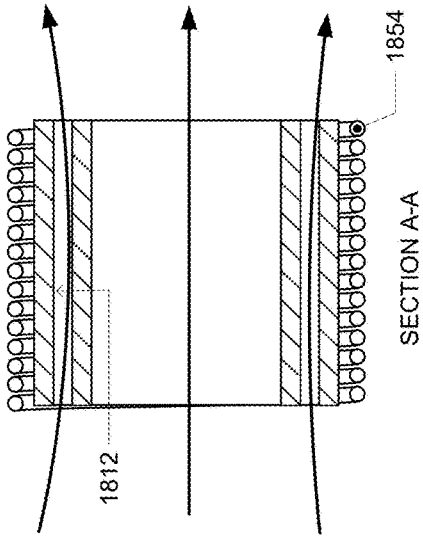

FIGURE 18c

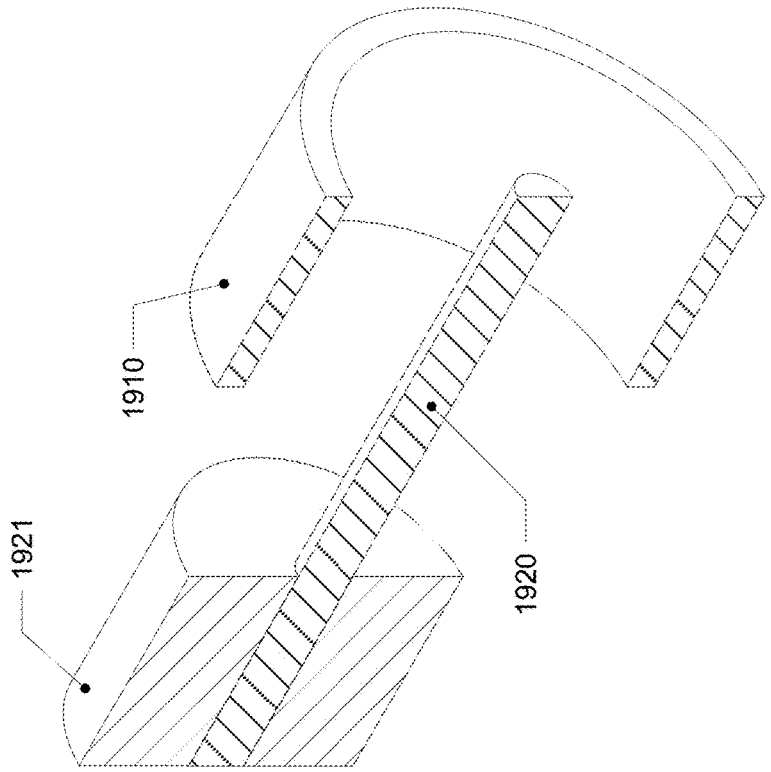

FIGURE 19b

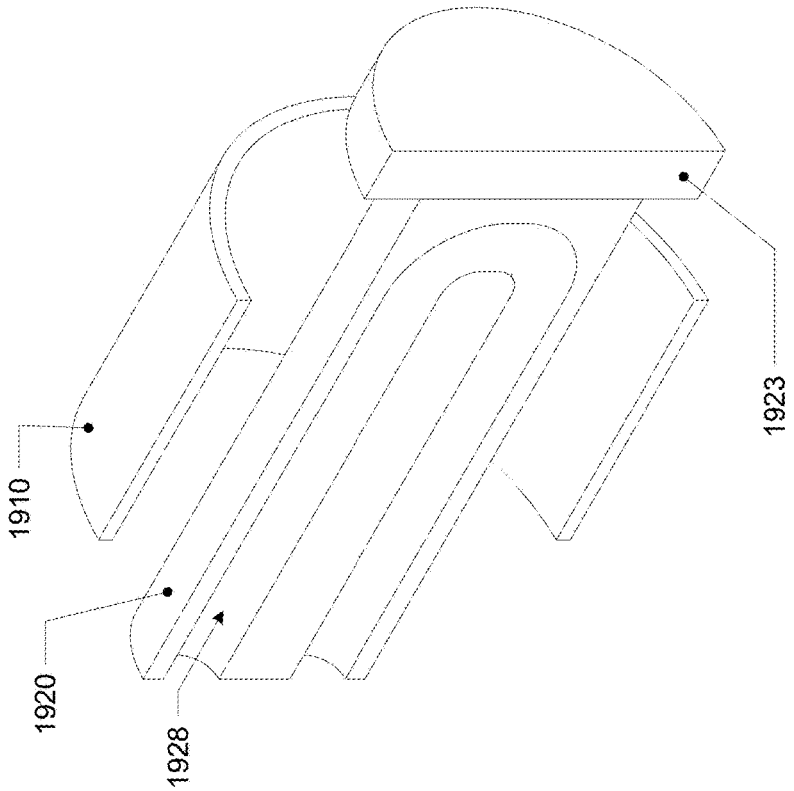

FIGURE 19a

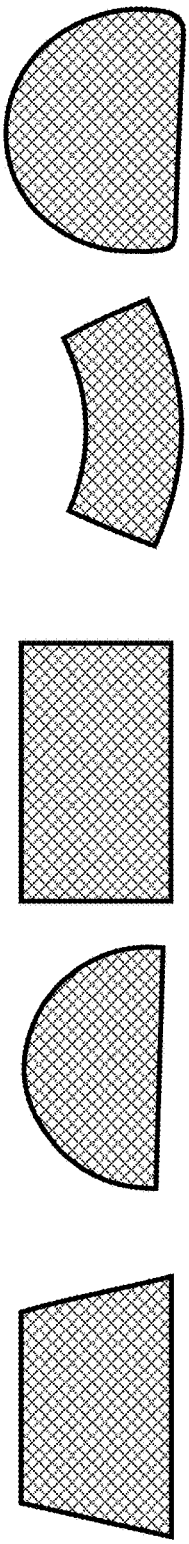

FIGURE 20a

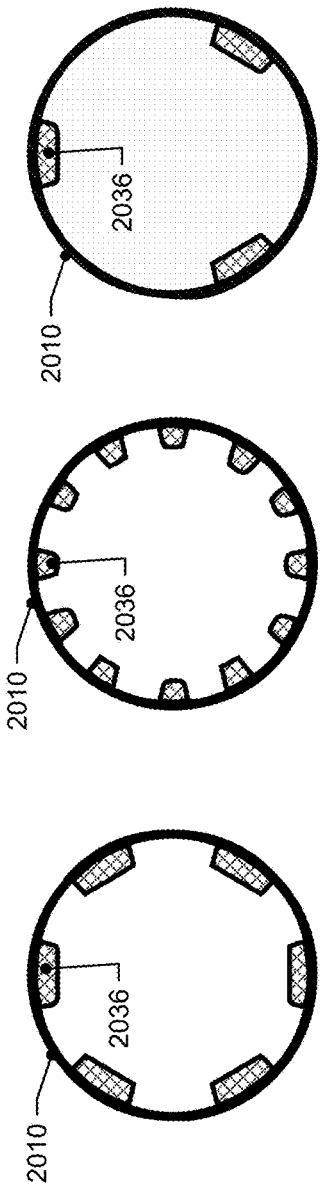

FIGURE 20b

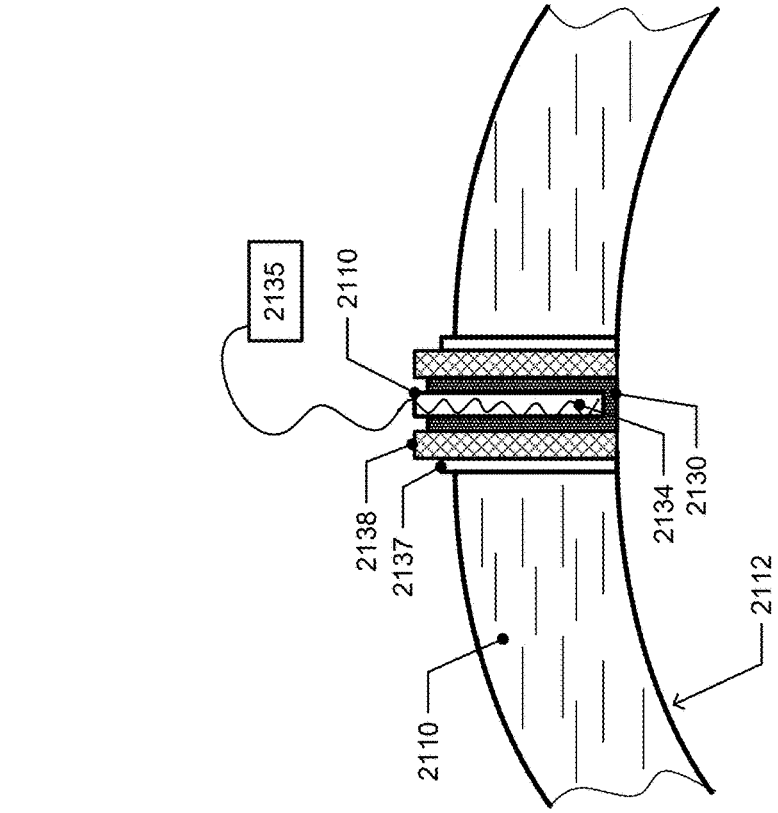

FIGURE 21b

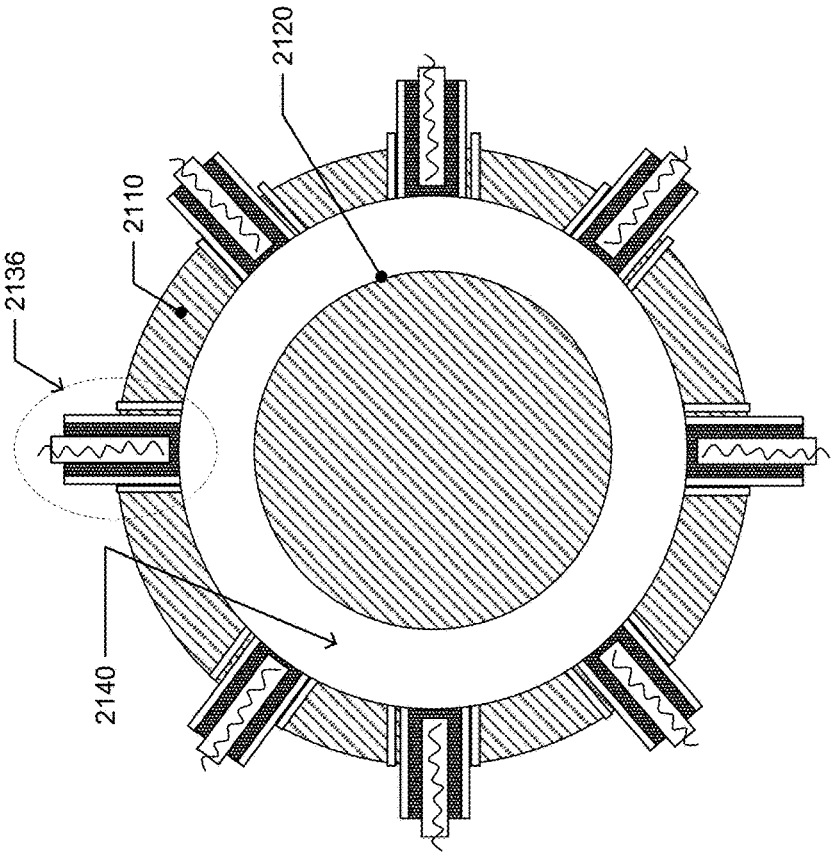

FIGURE 21a

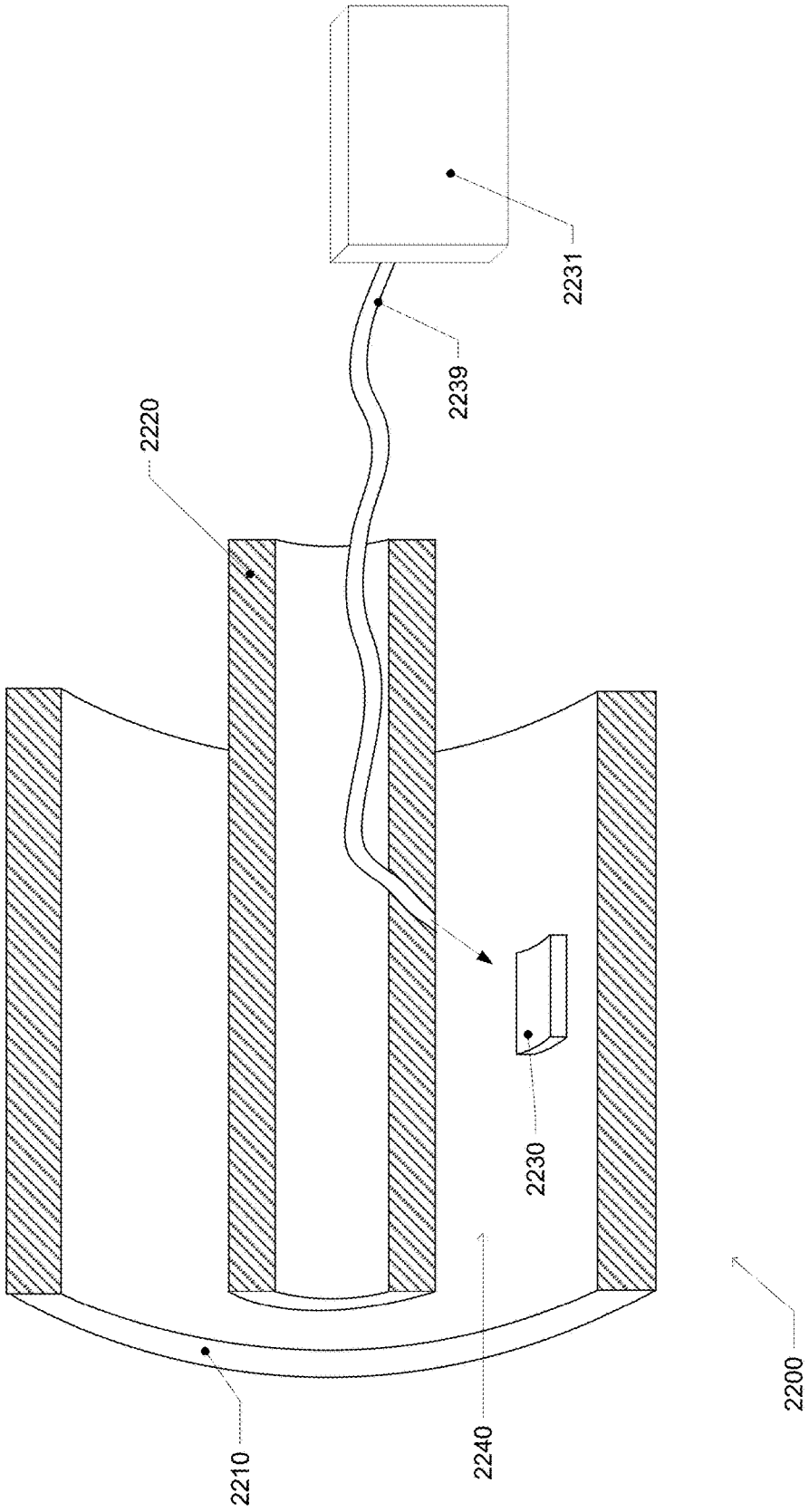

FIGURE 22

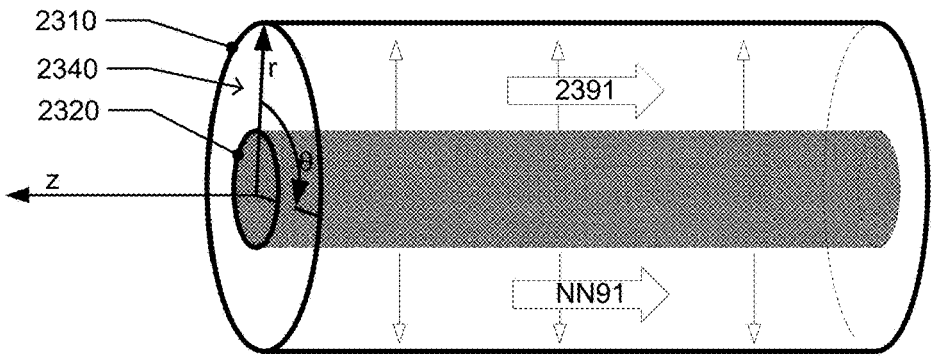

FIGURE 23a

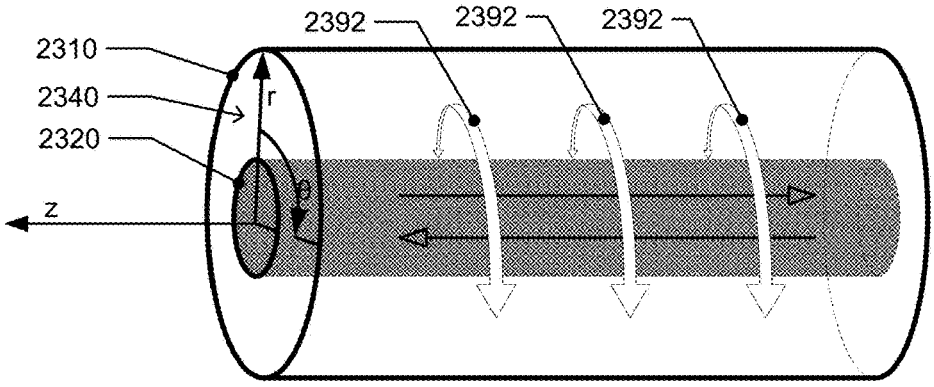

FIGURE 23b

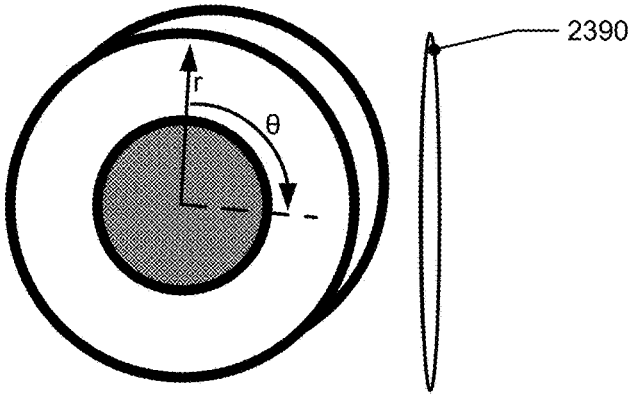

FIGURE 23c

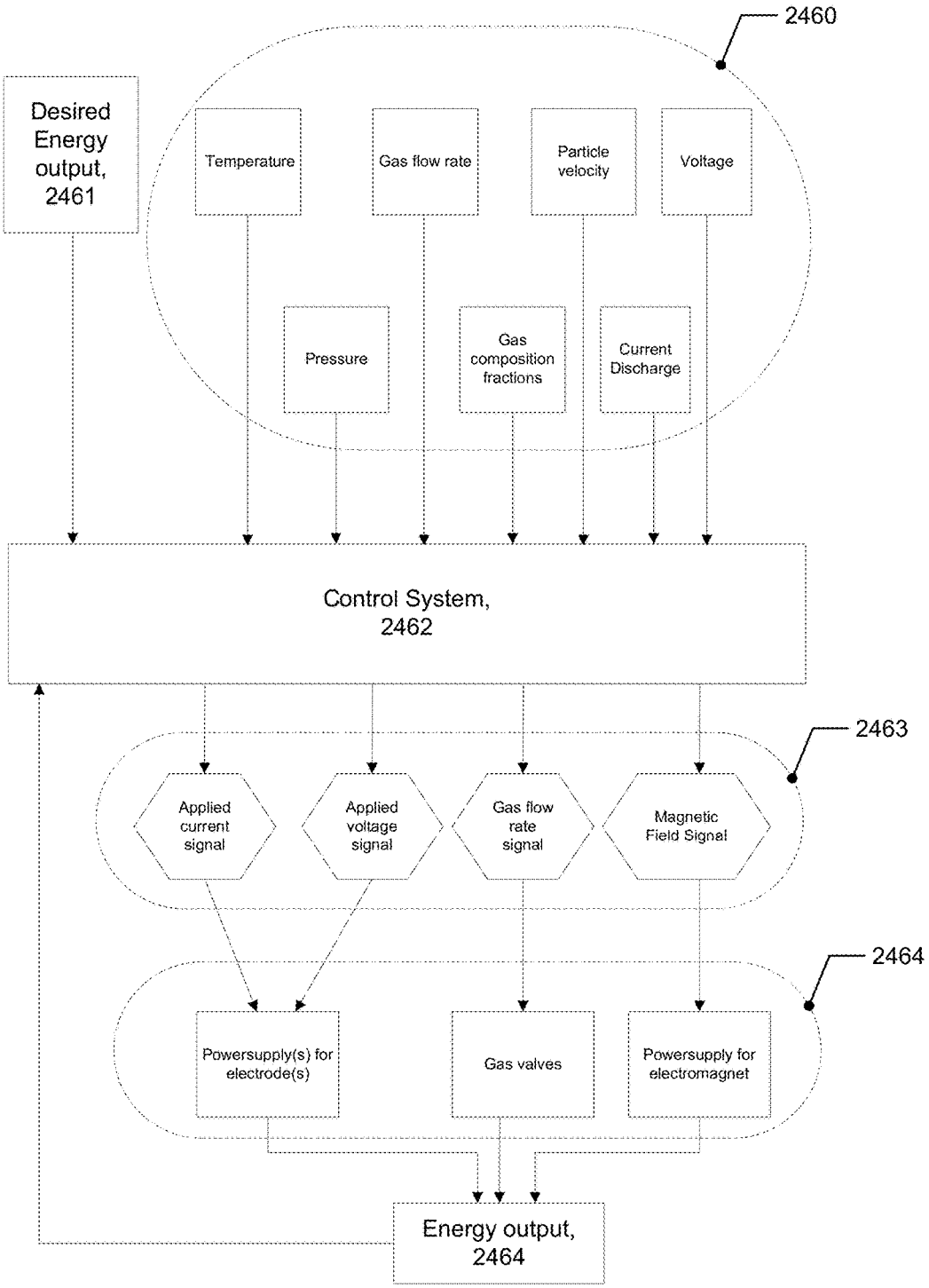
2460
Desired Energy output, 2461
Temperature
Gas flow rate
Particle velocity
Voltage
Pressure
Gas composition fractions
Current Discharge
Control System, 2462
2463
Applied current signal
Applied voltage signal
Gas flow rate signal
Magnetic Field Signal
2464
Powersupply(s) for electrode(s)
Gas valves
Powersupply for electromagnet
Energy output, 2464

FIGURE 24

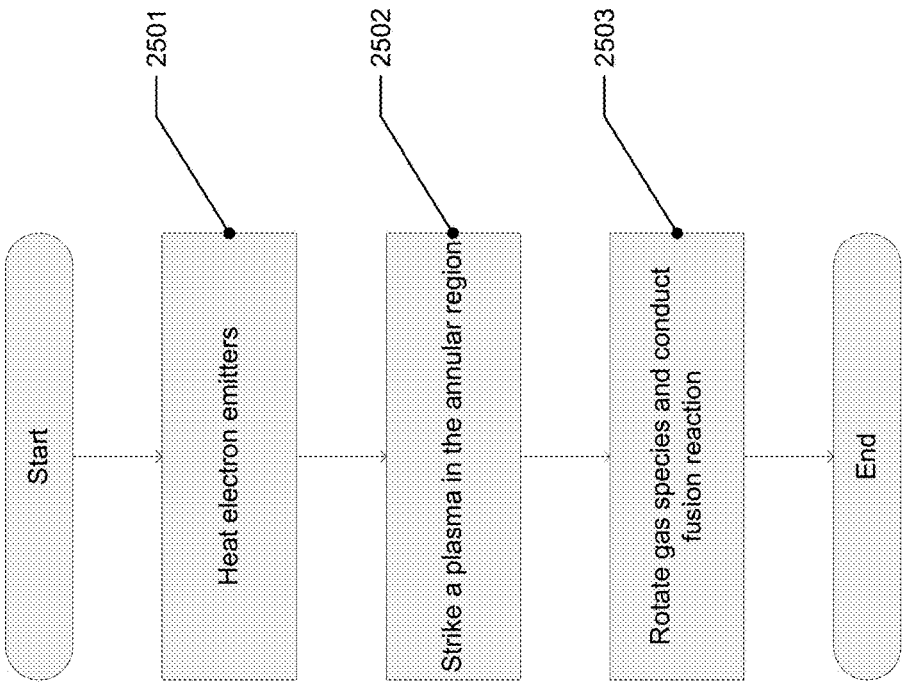
Start
2501
Heat electron emitters
2502
Strike a plasma in the annular region
2503
Rotate gas species and conduct fusion reaction
End

FIGURE 25

REACTOR USING ELECTRICAL AND MAGNETIC FIELDS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation in part of U.S. patent application Ser. No. 14/318,246, filed Jun. 27, 2014, which claims the benefit of (i) U.S. provisional application Ser. No. 61/840,428 having a filing date of Jun. 27, 2013; (ii) U.S. provisional application Ser. No. 61/925,114 filed Jan. 8, 2014; (iii) U.S. provisional application Ser. No. 61/925,131 filed Jan. 8, 2014; (iv) U.S. provisional application Ser. No. 61/925,122 filed Jan. 8, 2014; (v) U.S. provisional application Ser. No. 61/925,148 filed Jan. 8, 2014; (vi) U.S. provisional application Ser. No. 61/925,142 filed Jan. 8, 2014; (vii) U.S. provisional application Ser. No. 61/841,834 filed Jul. 1, 2013; (viii) U.S. provisional application Ser. No. 61/843,015 filed Jul. 4, 2013; U.S. patent application Ser. No. 14/318,246 is also a continuation-in-part of U.S. patent application Ser. No. 14/205,339 filed Mar. 11, 2014, now U.S. Pat. No. 9,245,654 issued Jan. 26, 2016, which claims benefit of U.S. provisional application Ser. No. 61/776,592 filed Mar. 11, 2013; and U.S. patent application Ser. No. 14/205,339 is a continuation-in-part of U.S. application Ser. No. 12/850,633 filed Aug. 5, 2010. The entire disclosures of each of these priority applications are incorporated herein by reference for all purposes.

Some aspects of the disclosed subject matter and the claimed invention may have been made by or on behalf of Alpha Ring International, Ltd. of Monterey, Calif. and Nonlinear Ion Dynamics, LLC of Monterey, Calif., under a joint research agreement titled "JOINT RESEARCH AND DEVELOPMENT AGREEMENT." The subject matter disclosed was developed and the claimed invention was made by, or on behalf of, one or both parties to the joint research agreement that was in effect on or before the effective filing date of the claimed invention, and some aspects of the claimed invention may have been made as a result of activities undertaken within the scope of the joint research agreement.

FIELD OF THE INVENTION

The present disclosure relates to inter-nuclear reactions and reactors for initiating and maintaining these reactions.

BACKGROUND

Since the 1950s, the science and technology communities have been striving to achieve controlled and economically viable fusion. Fusion is an appealing energy source for many reasons, but after billions of dollars and decades of research, to most, the idea of a sustainable fusion source for clean energy has become a pipe dream. The challenge has been to find a way to sustain a fusion reaction in a way that is economical, safe, reliable, and environmentally sound. This challenge has proved to be extraordinarily difficult. The commonly held belief in the art is that another 25-50 years of research remain before fusion is a viable option for power generation—"As the old joke has it, fusion is the power of the future—and always will be" ("Next ITERation?", Sep. 3, 2011, *The Economist*).

Prior efforts in large-scale fusion research have primarily focused on two methods of creating conditions for fusion ignition: inertial confinement fusion (ICF) and magnetic confinement fusion. ICF attempts to initiate a fusion reaction by compressing and heating fusion reactants such as a mixture of deuterium and tritium in the form of a small pellet about the size of a pinhead. The fuel is energized by delivering high-energy beams of laser light, electrons, or ions to the fuel target, causing the heated outer layer of the target fuel to explode and produce shockwaves that travel inward through the fuel pellet compressing and heating the fusion reactants, thereby initiating a fusion reaction.

At the time of this filing, the most successful ICF program is the National Ignition Facility (NIF) which was constructed at the cost of nearly 3.5 billion dollars and completed in 2009. NIF reached a milestone by causing a fuel pellet to give off more energy than was applied to it, but as of 2015, the NIF experiments were only able to reach about ⅓ of the energy levels needed for ignition. Regarding a sustainable reaction, the longest reported ICF fusion reaction was on the order of 150 picoseconds. Even if ICF efforts achieve ignition conditions, there are still many obstacles to making it a viable energy source. For example, solutions are needed to remove heat from the reaction chamber without interfering with the fuel targets and driver beams, and solutions are needed to mitigate the short lifetime of fusion plants due to the radioactive byproducts of the fusion reactants: deuterium and tritium reactions produce neutrons.

The second major research direction, magnetic confinement fusion, attempts to induce fusion by using magnetic fields to confine hot fusion fuel in the form of a plasma. This method seeks to lengthen the time that ions spend close together and increase the likelihood that they fuse. Magnetic fusion devices apply a magnetic force on charged particles in a manner that, when balanced with centripetal force, causes the particles to move in circular or helical path within the plasma. The magnetic confinement prevents the hot plasma from contacting the walls of its reactor. In magnetic confinement, fusion occurs entirely within the plasma.

Most of the research in magnetic confinement is based on the tokamak design in which hot plasma is confined within a toroidal magnetic field. The Tokamak Fusion Test Reactor (TFTR) at Princeton, N.J. is world's first magnetic fusion device to perform extensive scientific experiments with plasmas composed of 50/50 deuterium/tritium. Built in 1980, it was hoped that TFTR would finally achieve fusion energy, but it never achieved this goal and was shut down in 1997. To date, the longest plasma duration time of any tokamak is 6 minutes and 30 seconds, held by the Tore Supra tokamak in France. Current efforts in magnetically confined fusion are focused on the International Thermonuclear Experimental Reactor (ITER), a Tokamak reactor that began construction in 2013. As of June 2015, the building costs have exceeded $14 billion, and construction of the facility is not expected until 2019 with full deuterium-tritium experiments starting in 2027. The current estimate for the cost of the project is over $50 billion, and it is likely the costs will continue to rise. Recently, the Energy and Water Development Subcommittee of the Senate Appropriations Committee released a recommendation that the U.S. withdraw from the ITER project. Due to market realities, and the inherent limitations of the tokamak design for fusion power, many analysts doubt that fusion reactors such as ITER will become commercially viable.

An alternative form of magnetic confinement is being studied by the Maryland Centrifugal Experiment (MCX), at the University of Maryland. It will test the concepts of centrifugal confinement and velocity shear stabilization. In this experiment, capacitors are discharged from a cylindrical cathode through hydrogen gas to a surrounding vacuum chamber in the presence of a magnetic field. The orthogonal

electric and magnetic fields (represented as J×B) produce a force that drives hot ionized plasma (>10^5 K) into rotation around the discharge electrodes. Due to the significant change in temperatures at the plasma boundary, there inevitably exists cold neutral species that significantly affect plasma flows. Studies have focused on the effect of neutrals and as they have thought to "impede the required plasma rotation" needed for fusion conditions. "Neutral species" or simply "neutrals" are atoms or molecules with a neutral charge, i.e., they have the same number of electrons and protons, the atomic number in the case of an atom. An ion or ionized atom or other particle has a charge, i.e., it has at least one more electron than proton or at least one more proton than electron.

Rotating plasma devices that do not employ highly ionized plasmas have been considered for fusion research, but the neutrals have always been seen as a problem for reaching fusion conditions. Due to limiting effects including neutral drag and instabilities, one researcher in the field considered that while "not quite impossible [it is] still unlikely that rotating plasmas alone would lead to the realization of a self-sustained fusion reactor." (Review Paper: ROTATING PLASMAS", Lehnart, Nuclear Fusion 11 (1971)).

All credible prior approaches have all faced confinement and engineering issues. A gross energy balance for a fusion reactor, Q, is defined as:

$$Q=E_{fusion}/E_{in},$$

where E_{fusion} is the total energy released by fusion reactions, and E_{in} is the energy used to create the reactions. The goal is to exceed a Q of one or "unity" toward the end of creating a viable energy source. Officials of the Joint European Torus (JET) claim to have achieved Q≈0.7 and the US National Ignition Facility recently claims to have achieved a Q>1 (ignoring the very substantial energy losses of its lasers). The condition of Q=1, referred to as "breakeven," indicates that the amount of energy released by fusion reactions is equal to the amount of energy input. In practice, a reactor used to produce electricity should exhibit a Q value significantly greater than 1 to be commercially viable, since only a portion of the fusion energy can be converted to a useful form. Conventional thinking holds that only strongly ionized plasmas that do not have significant quantities of neutrals present have the potential of achieving Q>1. These conditions limit the particle densities and energy confinement times that can be achieved in a fusion reactor. Thus, the field has looked to the Lawson criterion as the benchmark for controlled fusion reactions—a benchmark, it is believed, that no one has yet achieved when accounting for all energy inputs. The art's pursuit of the Lawson criterion, or substantially similar paradigms, has led to fusion devices and systems that are large, complex, difficult to manage, expensive, and, as yet, economically unviable. A common formulation of the Lawson criterion, known as the triple product, is as follows:

$$nT\tau_E > \frac{12k_B}{E_{ch}}\frac{T^2}{\langle\sigma v\rangle}$$

While the Lawson criterion will not be discussed in detail here; in essence, the criterion states that the product of the particle density (n), temperature (T), and confinement time (τ_E) must be greater than a number dependent on the energy of the charged fusion products (E_{ch}), the Boltzmann constant (k_B), the fusion cross section (σ), the relative velocity (v), and temperature in order for ignition conditions to be reached. For the deuterium-tritium reaction, the minimum of the triple product occurs at T=14 keV and the number for the triple product is about 3×10^{21} keV s/m^3 (J. Wesson, "Tokamaks", Oxford Engineering Science Series No 48, Clarendon Press, Oxford, 2nd edition, 1997.) In practice, this industry-standard paradigm suggests that temperatures in excess of 150,000,000 degrees Centigrade are required to achieve positive energy balance using a D-T fusion reaction. For proton-boron 11 fusion, the Lawson criterion suggests that the required temperature must be yet substantially higher. More specifically, nτ~10^{16} s/cm^3, which is ~100× greater than required for D-T fusion [from *Inertial Electrostatic Confinement (IEC) Fusion: Fundamentals and Applications* by George H. Miley and S. Krupaker Murali].

An aspect of the Lawson criterion is based on the premise that thermal energy must be continually added to the plasma to replace lost energy, maintain the plasma temperature, and keep it fully or highly ionized. In particular, a major source of energy loss in conventional fusion systems is radiation due to electron bremsstrahlung and cyclotron motion as mobile electrons interact with ions in the hot plasma. The Lawson criterion was formulated for fusion methods where electron radiation loss is a significant consideration due to the use of hot, heavily ionized plasmas with highly mobile electrons.

Because the conventional thinking holds that high temperatures and a strongly-ionized plasma, absent of the presence of a significant presence of neutrals, are required, it was further believed that inexpensive physical containment of the reaction was impossible. Accordingly, the methods that have been most heavily pursued are directed to complex and expensive schemes to contain the reaction, such as those used in magnetic confinement systems (e.g., the ITER tokamak) and in inertial confinement systems (e.g., NIF laser).

In fact, at least one source acknowledges the believed impossibility of containing a fusion reaction with a physical structure: "The simplest and most obvious method with which to provide confinement of a plasma is by a direct-contact with material walls, but is impossible for two fundamental reasons: the wall would cool the plasma and most wall materials would melt. We recall that the fusion plasma here requires a temperature of ~10^8 K while metals generally melt at a temperature below 5000 K." ("Principles of Fusion Energy," A. A. Harms et al.). The need for extremely high temperatures is premised on the belief that only highly energized ions with charge can fuse, and that the coulombic repulsion force limits the fusion events. The present teaching in the field relies on this basic assumption for the vast majority of all research and projects.

In rare instances, researchers have considered methods for reducing the Coulombic barrier or repulsion force, which repels interacting positive nuclei, in order to reduce the required energy to initiate and maintain fusion. Such methods have largely been disregarded as infeasible with the methods described above.

In the 1950's the concept of muon-catalyzed fusion was studied by Luis Alvarez using a hydrogen bubble chamber at the University of California at Berkeley. Alverez's work ("Catalysis of Nuclear Reactions by μ Mesons." Physical Review. 105, Alvarez, L. W.; et al. (1957)) demonstrated nuclear fusion taking place at temperatures significantly lower than the temperatures required for thermonuclear fusion. In theory, it was proposed that fusion could occur even at or below room temperature. In this process, a negatively charged muon replaces one of the electrons in a

hydrogen molecule. Since the mass of a muon is 207 greater than an electron, the hydrogen nuclei are consequently drawn 207 times closer together than in a normal molecule. When the nuclei are this close together, the probability of nuclear fusion is greatly increased, to the point where a significant number of fusion events can happen at room temperature.

While muon-catalyzed fusion received some attention, efforts to make a muon-catalyzed fusion source have not been successful. Current techniques for creating large numbers of muons require significant amounts of energy that exceed the energy produced by the catalyzed nuclear fusion reactions, thus precluding breakeven or Q>1. Moreover, each muon has about a 1% chance of "sticking" to the alpha particle produced by the nuclear fusion of a deuteron (the nucleus of deuterium atom) with a triton (the nucleus of tritium atom), removing the "stuck" muon from the catalytic cycle. This means that each muon can only catalyze at most a few hundred deuterium-tritium nuclear fusion reactions. Thus, these two factors—muons being too expensive to make and then sticking too easily to alpha particles—limit muon-catalyzed fusion to a laboratory curiosity. To create useful muon-catalyzed fusion, reactors would need a cheaper, more efficient muon source and/or a way for each muon to catalyze many more fusion reactions. To date, none have been found or even theorized.

In March of 1989, Martin Fleischmann and Stanley Pons submitted a paper to the Journal of Electroanalytical Chemistry reporting that they had discovered a method of reducing the Coulombic barrier by a method that is now commonly referred to as "cold fusion." Fleishmann and Pons believed they had observed nuclear reaction byproducts and a significant amount of heat generated by a small tabletop experiment involving electrolysis of heavy water on the surface of palladium electrodes. One explanation for cold fusion considered that hydrogen and its isotopes could be absorbed in certain solids, such as palladium, at high densities. The absorption of hydrogen creates a high partial pressure, reducing the average separation of hydrogen isotopes and thus lowering the potential barrier. Another explanation was that electron screening of the positive hydrogen nuclei in the palladium lattice was sufficient for lowering the barrier.

While the Fleischmann-Pons findings initially received significant press, the reception by the scientific community was largely critical as a group at Georgia Tech University quickly found problems with their neutron detector, and Texas A&M University discovered bad wiring in their thermometers. These experimental mistakes, along with many failed attempts to replicate the Fleischmann-Pons experiment by well-known laboratories, lead most in the scientific community to conclude that any positive experimental results should not be attributed to "fusion." Due in part to the publicity received, the United States Department of Energy (DOE) organized a special panel to review cold fusion theory and research. First in November of 1989, and again 2004, the DOE concluded that results thus far did not present convincing evidence that useful sources of energy would result from the phenomena attributed to "cold fusion."

Another attempt to reduce the Coulombic barrier employs electron screening in a solid matrix. Electron screening has first been observed in stellar plasmas where it was determined to change the fusion rate by five orders of magnitude if the screening factor changes by only a few percent (Wilets, L., et al. "Effect of screening on thermonuclear fusion in stellar and laboratory plasmas." The Astrophysical Journal 530.1 (2000): 504.). According to Wilets, "[t]he rate of thermonuclear fusion in plasmas is governed by barrier penetration. The barrier itself is dominated by the Coulomb repulsion of the fusing nuclei. Because the barrier potential appears in the exponent of the Gamow formula, the result is very sensitive to the effects of screening by electrons and positive ions in the plasma. Screening lowers the barrier and thus enhances the fusion rate; the greater the nuclear charges, the more important it becomes."

One example that tries to make use of this electron screening effect to create ignition conditions is presented in US Patent Publication No. US2005/0129160A1 by Robert Indech. In this application, Indech describes the electron shielding of the positively-charged repulsive forces between two deuterons located near the tip of a microscopic cone structure when electrons concentrate at the top of the cone structure due to an applied potential. As disclosed, these cones were arrayed on a surface measuring 3 cm by 3 cm.

While Indech and others have realized the potential electron screening to lower the Coulombic barrier for fusion reactors, it is doubtful any efforts have been successful. At most these efforts appear to propose methods for ignition and not a sustained and controlled fusion reaction. Despite efforts in ICF, magnetic confinement fusion, and various methods of reducing the Coulombic barrier, there is currently no commercially feasible fusion reactor design that exists.

SUMMARY OF INVENTION

One aspect of the present disclosure relates to an apparatus having features (a)-(f). Feature (a) is a first electrode having a substantially cylindrical inner surface that has an axis and forms at least a portion of a confining wall, where the confining wall at least partially encloses a confinement region. Feature (b) is a second electrode located within a region interior to the first electrode and separated from the from the first electrode by at least the confinement region. Feature (c) includes at least one magnet configured to provide a magnetic field through the confinement region such that at least a portion of the magnetic field in the confinement region is substantially parallel to the axis of the substantially cylindrical inner surface of the first electrode. Feature (d) is an inlet to the confinement region for permitting introduction of neutral particles to the confinement region. Feature (e) is a control system including a voltage and/or current source for applying a potential difference between the first electrode and the second electrode that is sufficient to produce an electrical current from the first electrode to the second electrode in the confinement region, where the first and second electrodes, the at least one magnet, and/or the control system are configured to induce rotational movement of charged particles and neutral particles in the confinement region. Feature (f) is a reactant attached to or embedded in the second electrode such that, during operation, repeated collisions between the neutral particles and the reactant produce an interaction that gives off energy and produces a product having a nuclear mass that is different from a nuclear mass of any of the nuclei of the neutral particles, and the reactant.

In some cases, the control system may be configured to control the magnetic field in the confinement region and/or control a supply of neutrals to the confinement region via the inlet. The first and second electrodes, the at least one magnet, and/or the control system of the apparatus may sometimes be configured to induce rotational movement of

the neutral particles in the confinement region at an average velocity of at least about 10,000 m/s in the confinement region.

In some embodiments, the second electrode has a diameter of at most about 0.5 inches, and in some cases, the second electrode is a filament. When the diameter of the second electrode has a diameter of at most about 0.5 inches, the electrode may be held by a conductive sleeve.

In some embodiments, the second electrode has a length in a direction parallel to the axis of the substantially cylindrical inner surface of the first electrode, and said length being between about 3 cm and about 10 cm.

In some embodiments, the apparatus includes a ceramic block that is thermally coupled to the second electrode and configured to remove thermal energy from the second electrode via conduction. In some embodiments, the second electrode has a passage configured to remove thermal energy from the second electrode via convection. In some embodiments, the apparatus includes a linear actuator that is configured to move the second electrode in a direction that is substantially parallel to the axis of the substantially cylindrical inner surface of the first electrode.

In some embodiments, the first electrode and the second electrode are separated by a gap of between about 0.1 mm and about 20 cm. In some embodiments, the second electrode may include tungsten, copper, tantalum, lanthanum hexaboride, and/or carbon.

In some embodiments, the at least one magnet includes at least one permanent magnet having opposite magnetic poles offset from one another in the direction of the axis of the substantially cylindrical inner surface of the first electrode. In some embodiments, the at least one magnet includes two permanent magnets separated from one another by at least the confinement region and in the direction of the axis of the substantially cylindrical inner surface of the first electrode. In some embodiments, the at least one magnet includes two permanent magnets radially separated from one another by at least the confinement region. In some embodiments, the at least one magnet includes an electromagnet. An electromagnet may be in, e.g., a superconducting magnet.

In some embodiments, the at least one magnet may be configured to generate a magnetic field that is greater than about 0.5 Tesla in the confinement region.

In some embodiments, at least a portion of the confining wall may be separable from the remainder of the apparatus which may be configured to allow replacement of the at least a portion of the confining wall that is separable.

In some embodiments, the second electrode may be coated with an electron emitting material. In some cases, the reactant includes boron 11. In some cases, the neutral particles are introduced by the inlet to achieve a pressure of between about 0.5 atm and about 1.5 atm within the confinement region. In some cases, an apparatus may include a pump that is configured to reduce pressure within the confinement region. For example, a pump may be configured to reduce the pressure within the confinement region to less than about 20 torr.

In some embodiments, the confining wall includes a refractory metal and/or a stainless steel. In some embodiments, the confining wall includes a layered structure in which at least one the layers includes the first electrode. The outer layer of the layered structure may in some cases be an electrically insulating layer.

In some cases, the nuclear mass of the product is greater than the nuclear mass of any of the nuclei of the neutral particles and the reactant. In some cases, the interaction is a fusion reaction, and in some cases, the fusion reaction is an aneutronic fusion reaction. In some embodiments, the reactant attached to or embedded in the confining wall includes boron-11 and/or the neutrals include neutral hydrogen, deuterium, and/or tritium.

In some embodiments, during operation, the neutrals in the confinement region proximate the confining wall may have a concentration of at least about $10^{20}/cm^3$. In some embodiments, during operation, the neutrals in the confinement region proximate the second electrode may have a concentration of at least about $10^{20}/cm^3$.

In some embodiments, the apparatus also has one or more electron emitters configured to emit, during operation, electrons into an electron-rich region adjacent to the second electrode. This electron-rich region may extend, in some cases, from the second electrode into the confinement region by a distance of between about 50 nanometers to about 50 micrometers, and in some cases the electron-rich region may extend by a distance up to about 3 millimeters. In some cases, the electron emitters comprise boron or a boron-containing material.

In some embodiments, the confinement region proximate the second electrode includes an electron-rich region having at least about $10^6/cm'$ more electrons than positively charged particles. During operation, the electron-rich region may have an electric field strength of at least about 10^6 V/m, and in some cases, the neutrals in the electron-rich region have an energy of, on average, of between about 0.1 eV and 2 eV.

In some embodiments, the control system may be configured to supply a potential to the first electrode or the second electrode using constant current. In some, embodiments, the voltage and/or current source includes a capacitor or a battery. In some embodiments, the apparatus includes an outlet valve near the confining wall for removing the product of the interaction.

Another aspect of the present disclosure relates to a method of operations (a)-(d). Operation (a) consists of introducing neutral particles to a confinement region. Operation (b) includes applying an electric potential difference between a first electrode and a second electrode to produce an electrical current from the first electrode toward the second electrode, where the first electrode has a substantially cylindrical inner surface that has an axis and forms at least a portion of a confining wall that at least partially encloses the confinement region. The second electrode has a reactant attached to it or embedded in it, and the second electrode is located within a region interior to the first electrode and separated from the from the first electrode by at least the confinement region. Operation (c) includes applying a magnetic field, from at least one magnet, through the confinement region such that at least a portion of the magnetic field in the confinement region is substantially parallel to the axis of the substantially cylindrical inner surface of the first electrode so that ions and neutral particles are rotated in the confinement region. Operation (d) includes maintaining rotational movement of the neutral particles to promote repeated collisions between the neutral particles and the reactant to thereby produce a reaction between the reactant and the neutral particles that gives off energy and produces a product having a nuclear mass that is different from a nuclear mass of any of the nuclei of the neutral particles and the reactant.

In some cases, when performing this method, the neutral particles travel in the confinement region at an average velocity of at least about 10,000 m/s.

In some cases, the second electrode may have a diameter of at most about 0.5 inches, and in some cases, the second

electrode is a filament. In some cases, the second electrode includes tungsten, copper, tantalum, lanthanum hexaboride, and/or carbon.

In some cases, the at least one magnet includes at least one permanent magnet having opposite magnetic poles offset from one another in the direction of the axis of the substantially cylindrical inner surface of the first electrode. In some cases, the at least one magnet includes two permanent magnets separated from one another by at least the confinement region and in the direction of the axis of the substantially cylindrical inner surface of the first electrode. In some cases, the at least one magnet includes two permanent magnets radially separated from one another by at least the confinement region. In some cases, the at least one magnet includes an electromagnet, and in some cases, the electromagnet is a superconducting magnet.

In some cases, the method includes an operation of separating at least a portion of the confining wall from the at least one magnet to allow replacement of the at least a portion of the confining wall. In some cases, the second electrode is coated with an electron emitting material. In some cases, the second electrode is coated with boron or a boron-containing material. In some cases, the pressure in the confinement region may be between about 0.5 atm and 1.5 atm.

In some cases, the confining wall may include a refractory metal and/or a stainless steel. In some cases, the confining wall includes a layered structure in which at least one the layers includes the first electrode.

In some cases, the nuclear mass of the product may be greater than the nuclear mass of any of the nuclei of the neutral particles and the reactant. In some cases, the reaction is a fusion reaction, and in some cases, the reaction is an aneutronic fusion reaction. In some cases, the reactant attached to or embedded in the second electrode includes boron 11. In some cases, the neutral particles include neutral hydrogen, deuterium, and/or tritium. In some cases, the method is performed so that neutrals in the confinement region proximate the confining wall have a concentration of at least about $10^{20}/cm^3$.

In some cases, the method includes emitting electrons from one or more electron emitters configured to, during operation, emit electrons into a region adjacent to the second electrode. The electron emitters may include boron or a boron-containing material.

In some cases, the method includes producing an electron-rich region in the confinement region proximate the second electrode, where the electron-rich region has an excess of electrons over positively charged particles of at least about $10^6/cm^3$. The electron-rich region may, in some cases, extend from the second electrode into the confinement region by a distance of between about 50 nanometers and about 50 micrometers, and in some cases, the electron-rich region may extend by a distance up to about 3 millimeters. In some cases, the electron-rich region may have an electric field strength of at least about 10^6 V/m and in some cases, the neutrals in the electron-rich region have an energy of, on average, of between about 0.1 eV and 2 eV.

In some cases, the second electrode may be held by a conductive sleeve. In some cases, the second electrode may be cooled by passing a fluid through it. In some cases, the method may include moving the second electrode in a direction parallel to the axis of the substantially cylindrical inner surface of the first electrode. In some cases, when conducting the method, the neutral particles may be introduced to the confinement region at a pressure less than about 20 torr. In some cases, the electric field between the first electrode and the second electrode may be applied using a constant current, and in some cases, the electric field may be applied using a capacitor or a battery. In some cases, the method includes removing the product of the reaction.

BRIEF DESCRIPTION OF DRAWINGS

FIGS. **1***a-c* depict several views of a first embodiment reactor.

FIGS. **2***a-b* schematically illustrate the movement of charged particles and neutral particles rotating within a confinement wall.

FIGS. **3***a-d* schematically depict neutral and charged particle interactions with a confinement wall.

FIGS. **4***a-e* depict stages of the aneutronic proton-boron-11 fusion reaction.

FIGS. **5***a-d* depict a reverse electrical polarity reactor.

FIGS. **6***a-f* depict a hybrid reactor.

FIGS. **7***a-b* depict a wave-particle reactor.

FIGS. **8***a-b* depict various electrode configurations of a first embodiment reactor.

FIGS. **9***a-c* depict various cross sections of a first embodiment reactor.

FIGS. **10***a-d* depict a first embodiment reactor in which an axial magnetic field is applied by a superconducting magnet.

FIGS. **11***a-b* depict a first embodiment reactor in which permanent magnets are configured to apply an axial magnetic field in a first embodiment reactor.

FIGS. **12***a-b* depict a first embodiment reactor in which the applied magnetic field in the confinement region is applied using permanent magnets.

FIGS. **13***a-c* depict a configuration of a first embodiment reactor.

FIGS. **14***a-c* depict a configuration of a first embodiment reactor.

FIGS. **15***a-c* depict how ring magnets may be positioned along a common axis create a magnetic field substantially pointed along that axis.

FIGS. **16***a-c* depict a first embodiment reactor in which the applied magnetic field in the confinement region is applied using ring magnets.

FIGS. **17***a-c* depict a first embodiment reactor in which the applied magnetic field in the confinement region is applied using radially offset magnets.

FIGS. **18***a-d* depict a first embodiment reactor in which the applied magnetic field in the confinement region is applied using an electromagnet.

FIGS. **19***a-b* depict various embodiments of a reverse electrical polarity reactor.

FIGS. **20***a-b* depict various electron emitters that may be placed on a confinement wall.

FIGS. **21***a-b* depict electron emitting modules that may be placed on a confinement wall of a reactor.

FIG. **22** depicts a reactor configured with a laser increasing or controlling electron emission from an electron emitter.

FIGS. **23***a-c* depicts a configuration where nuclear magnetic resonance sensing is used to determine the composition of gas reactants within a reactor.

FIG. **24** depicts how a control system may be configured to operate a reactor using closed-loop feedback.

FIG. **25** depicts an example of a multistage process flow that may be used to operate a reactor

DETAILED DESCRIPTION

Introduction

Various embodiments disclosed herein pertain to reactors and methods of operating those reactors under conditions

that induce a reaction between two or more nuclei in a manner that produces more energy than is input to the reactor. This disclosure refers to such reactions as nuclear fusion reactions or simply fusion reactions, although aspects of the reaction may be quantitatively or qualitatively different from aspects of reactions conventionally characterized as nuclear fusion. Therefore when the term fusion is used in the remainder of this disclosure, the term does not necessarily connote all the features conventionally ascribed to nuclear fusion. In some embodiments disclosed herein, a reactor may generate a sustained fusion reaction making it suitable as a viable energy source. As described herein, a sustained fusion reaction refers to a fusion reaction in which reactor may continuously operate above unity for a period of about a second.

In various embodiments, the reactor in which the fusion reaction occurs is designed or configured to constrain or confine rotating species including, typically, one or more of the nuclei participating in a fusion reaction. Various structures may be provided for confining the rotating species. Typically, though not necessarily, these structures define a solid physical enclosure. As explained more fully elsewhere herein, the enclosed structure may have many shapes such as a generally cylindrical shape. Examples of suitable structures that may be used for a physical enclosure are depicted in FIGS. **1**, **7**, and **6**.

Regardless of any other functions, the wall of the reactor typically serves to confine species rotating in the region adjacent to and internal to the wall. The wall is confining in the sense that it confines the rotating species to remain within the reactor. As described herein, this wall of the reactor is referred to as the wall, the confining wall, or the shroud. In various embodiments, the wall also serves other functions: notably as an electrode, as a magnet, as a source of fusion reactants (e.g., boron compounds), and/or as an electron emitter. Because the wall constrains the reactants species physically rather than by a magnetic field or a pressure wave—as are done in conventional approaches to fusion—it is unlike any conventional fusion reactor designs. Its other functions, such as being an electrode for imparting a voltage difference, being a magnet, being a source of reactant material, and being an electron emitter, provide additional distinctions from conventional fusion reactor designs.

In certain embodiments, the reactor contains a wall, as described, and a space interior to the wall (which may be annular in shape) where reactant species, including a substantial fraction or percentage of neutrals, rotate and repeatedly impinge on the surface of the reactor wall and sometimes fuse with species present in the wall. When accounting for the energy input to the reactor, the resulting reaction can breakeven and result in Q>1. To ensure that the fusion reaction is sustainable over a period required by particular energy-generation applications, the ratio of energy out to energy in should be significantly greater than 1. This accounts for inherent inefficiencies in using energy generated by a fusion reaction to sustain the conditions that allow fusion to occur (e.g., particular plasma densities in the confinement region). In certain embodiments, the ratio should be at least about 1.2. In certain embodiments, the ratio should be at least about 1.5. In certain embodiments, the ratio should be at least about 2. In certain embodiments, the reactor is continuously operated under sustainable conditions for at least about fifteen minutes, or at least about one hour. In one example, hydrogen atoms rotate in the reactor and impinge on boron or lithium atoms in the reactor wall to undergo fusion. In some embodiments, the reactor includes one or more electron emitters that produce an electron flux that, during operation, produce a strong field that reduces the Coulombic repulsion between interacting nuclei.

The reactants can be any species that can support a fusion reaction in the space interior to the confining wall of the reactor. In various embodiments, at least one of the reactants is a species that is rotating within the reactor interior region. In some cases, both of the reactants are rotating species. In some cases, one of the reactants is a rotating species and the other is a species that is held stationary, such as when a reactant is embedded in a part of the reactor wall that confines the rotating species. In some cases, there is some combination of reactants that are rotating and stationary such that fusion may occur between rotating species or between a rotating species and a stationary species. In cases where the reacting species are predominantly rotating species, the physical structure of the reactor may be configured such that the rotating species need not substantially impinge on the inner surface of a wall of the reactor to support a fusion reaction. In some designs, the rotating species are constrained by a force such as a force that prevents them from substantially striking the reactor wall. In such designs, two rotating species fuse in the region interior to the confining wall (e.g., the confinement region) or along the surface of the wall. In some designs, a rotating species may fuse with a stationary species (e.g., a target material) located within the confinement region.

In certain embodiments, the reactants are species that react aneutronically. In other embodiments, the reactants are species that react neutronically. One or both of the reactants may also be a neutral, or uncharged, species. Sometimes the species present in the reactor are referred to as "particles." However, such species are only particles at the molecular or atomic scale.

The disclosed small-scale, e.g., table-top, aneutonic reactors require relatively little or no biological shielding from neutron radiation. Fusion reactions in reactors described herein may be characterized as "warm fusion," e.g., where fusion occurs in the temperature range of about 1000K to 3000K, and as such are much easier to handle compared to "hot fusion reactors" (e.g. those in tokamak reactors). Since the fusion is substantially aneutronic and "warm," materials and thus costs associated with "warm fusion" reactors may be significantly reduced. For instance, in some cases, a prototype reactor has been built for less than $50,000. Since radiation shielding and the industrial-grade hardware commonly used for hot plasma reactors may not be required, the disclosed small-scale reactors may also have a small weight and footprint.

The rotational motion of the species in the reactor may be imparted by a number of mechanisms. One mechanism imparts rotation via the application of interacting electric and magnetic fields. The interaction is manifest as a Lorentzian force that acts on charged particles in the reactor. Examples of reactor designs that can produce a Lorentzian force to act on charged species are depicted in FIGS. **1***a-c* and **6**. FIGS. **1***a-c* depict a Lorentzian driven reactor where the reactor has inner electrode **120**, and where the shroud (confining wall) is an outer electrode **110**. An electric field **144** between the electrodes in the presence of an applied magnetic field **146**, having a perpendicular component, causes a Lorentzian force on charge particles or charged species traveling in between the electrodes. This force drives them azimuthally into rotation as indicated in FIG. **1***c*. In another class of reactor design, rotational motion is imparted to charged species by applying a potential or a change in potential sequentially to a plurality of electrodes arranged

azimuthally around a wall of the reactor. An example of a suitable reactor design is shown in FIG. **7**.

In many implementations, the reactor is operated in a manner such that the rotating charged species interact with neutral species and impart angular momentum to those neutral species, thereby setting up rotational motion of the neutral species as well as the charged species within the reactor. In many implementations, the majority of rotating species are neutrals and the charged species are ionized particles such as a proton (p^+). As described herein, this process may be referred to as ion-neutral coupling. FIG. **2***a* schematically illustrates the ion-neutral coupling process in which a few charged particles **204** impart motion to the surrounding neutral particles **206**.

In various embodiments, the reactor is designed to emit electrons in an internally localized region of the reactor where fusion events are expected to occur. Referring again to FIG. **2***a*, these electrons may form an electron-rich region **232** near the confining wall **210**. The presence of excess electrons lowers the Coulomb barrier and thereby increases the probability of fusion. As explained elsewhere herein, emitting electrons in this manner can produce an electron-rich region that reduces the intrinsic Coulombic repulsion between two positively charged nuclei, which are candidates for fusion. In certain embodiments, the electron emission occurs at or adjacent to the wall that confines the rotating species within the reactor. In one example, electron emission is provided by passive structures such as boron-containing coupons or strips embedded in or attached to the confining wall of the reactor. Such passive structures emit electrons when the localized temperatures increase during operation of the reactor. In other embodiments, electron emission is implemented using active structures that are controlled independently of the heating produced during normal operation of the reactor. An example of an active structure for electron emission is depicted in FIGS. **21***a* and **21***b* and includes separately controlled resistive elements for heating the individual electron emitters.

Another aspect of this disclosure relates to structures or systems for capturing and converting energy produced by a fusion reaction within the reactor. One class of energy capture systems provides for direct capture of electrical energy produced by traveling alpha particles generated by the fusion reaction. This may be done by generating an applied electric field in the path of emitted alpha particles which causes the alpha particles to decelerate and generates an electric current in a circuit connected to the electrodes used to produce the electric field. Another class of energy capture systems provides for energy capture using heat engines such as those including a turbine, heat exchanger, or other conventional structure employed to convert thermal energy produced from the fusion reaction into mechanical energy. These and other energy capturing mechanisms will be discussed later in this disclosure.

Interactions by Neutrals with the Wall

Neutral species interacting with the wall of a reactor provide a different type of interaction than has been employed in conventional fusion studies. The repeated interactions take place over a relatively large volume, which may be the annular space next to the inner wall of or the inner surface of the confinement wall. Because the rotating neutrals frequently interact elastically with the wall at a shallow angle, e.g., at a glancing or grazing angle, they may immediately leave the wall and reenter the interior space with much of the energy they had upon entry. FIG. **2***b* illustrates an example trajectory path a neutral **206** may have as it moves along the surface of the confinement wall **210**. When a rotating neutral particle enters or strikes the wall, it typically encounters a potential fusion partner with which it may react or not. When it does not react, it re-enters the interior space where it continues on its rotational journey. In this manner, it repeatedly interacts with the surface of the wall, and in each such elastic collision little to no energy is lost.

Some particle-wall interactions that do not result in fusion are illustrated schematically in FIGS. **3***a-d*. While the figures depict interactions with $boron^{11}$ and/or titanium, these interactions may also occur when other reactant materials are used in the confinement wall. As illustrated in FIG. **3***a*, in some fraction of the neutral-wall interactions, the neutral particle experiences an elastic collision with a nucleus in the wall (in this case an atom of $boron^{11}$), and the rebounding neutral maintains most of the energy it had going into the interaction. Of all neutral-wall interactions, elastic collisions typically have that highest occurrence. In a much smaller fraction of the collisions, depicted in FIG. **3***b*, the nucleus of the neutral comes sufficiently close to the nucleus of an atom in the wall that the collision becomes inelastic as a result of tunneling that occurs when the two nuclei come into very close proximity. FIG. **3***c* depicts yet another interaction that may occur; in this case, a neutral penetrates into the wall. This type of collision may occur somewhat frequently when the confinement surface contains a material such as titanium or palladium that may absorb hydrogen molecules.

FIG. **3***d* depicts an inelastic collision of a charged particle, e.g., a proton, with the confining wall. This situation contrasts with the frequent elastic collisions that neutrals such as atomic hydrogen have with the confining wall (previously depicted in FIG. **3***a*). When a charged particle approaches and departs from the confining wall, the particle may experience Bremsstrahlung energy loss. This energy loss is caused by electrostatic interaction between the charged particle and electrons in the electron-rich region. As a result of the electrostatic forces, some kinetic energy is lost, and high energy electromagnetic radiation such as x-rays are emitted. In conventional fusion reactors that focus on trying to fuse ionized particles, Bremsstrahlung radiation may result in significant energy loss. By using a weakly ionized plasma having a high proportion of neutrals to ions, these losses are largely avoided.

In a certain fraction of tunneling interactions between the neutral nucleus in motion and the nucleus of an atom in the wall, fusion may occur. FIG. **4***a* depicts the stages of the aneutronic fusion reaction that occurs when a hydrogen atom or proton fuses with a boron 11 atom. First, in **482**, a proton traveling at high velocity collides with a boron 11 atom, and the two nuclei fuse to form an excited carbon nucleus, depicted in **483**. The excited carbon nucleus is short-lived, however, and decomposes into a beryllium nucleus and an alpha particle that is emitted having a kinetic energy of 3.76 MeV, as seen in **484**. Finally, in **485**, the newly formed beryllium nucleus almost immediately decomposes into two more alpha particles, each having a kinetic energy of 2.46 MeV. FIGS. **4***b-e* depict the various stages of the same proton-boron 11 fusion reaction shown in FIG. **4***a* in relation to the surface of the confining wall **412**. FIG. **4***a* depicts a proton traveling at high velocity towards a surface of boron 11 atoms on the confining wall. As the neutral hydrogen atom approaches the confining wall it passes through and the electron-rich region **432**, which partially screens the repulsive force between the two positively charged nuclei. FIG. **4***c* depicts the stage at which the neutral hydrogen has fused with a boron atom to form a carbon nucleus. In FIG. **4***d*, the carbon nucleus has decom-

posed into a beryllium nucleus one alpha particle. Lastly, in FIG. **4***e*, the beryllium nucleus decomposes, emitting two additional alpha particles. Because the potential reactants are neutral species rather than ions, most of their interactions with atoms in the surface of the confinement wall are elastic collisions. In contrast, a positively charged particle entering the wall will be deflected by electrostatic repulsive forces at a distance from other nuclei in the wall. These electrostatic interactions cause the charged particle to lose energy; i.e., the collisions are inelastic. A neutral particle, which has a positively charged nucleus screened to a degree by the orbital electrons, does not experience the same repulsive force. As a consequence, the neutral is more likely to directly impact another atom in the wall. The use of neutrals rather than ions, therefore, increases the likelihood of a fusion reaction, and when a fusion reaction does not occur, the neutral is more likely to rebound elastically with a higher energy than a corresponding ion.

Overall, the rotating neutral particles undergo many repeated interactions with the wall and those that are unproductive in producing a fusion reaction elastically rebound with relatively little energy loss. As mentioned, the neutrals tend to reemerge from the wall and with sufficient energy that they can enter into a next interaction with the wall which might be productive in creating a fusion reaction. Each of the interactions with the wall has a probability of resulting in a fusion reaction between the neutral nucleus and the nucleus of an atom in the wall.

Where the reactants are different species (e.g., ^{11}B and p^+), the rate of fusion per unit volume is given by

$$dN/dT = n_1 n_2 \sigma v$$

where n_1 and n_2 are the densities of the respective reactants, σ is the fusion cross section at a particular energy, and v is the relative velocity between the two interacting species. For a system in which at least one species rotates in a confinement region and repeatedly strikes a confining wall containing a second species, the values of the densities of the species may be on the order of 10^{20} cm^{-3} for the rotating species and 10^{23} cm^{-3} for the immobilized species (e.g., boron), the values of the fusion cross section may be on the order of 10^{-32} cm^2, and the relative velocity of the interacting species may be on the order of 10^3 m/s. By comparison, for a tokamak reactor, the values of the density of each of the species is on the order of 10^{14} cm^{-3}, the values of the fusion cross section are on the order of 10^{-28} cm^2, and the relative velocity of the interacting species is on the order of 10^6 m/s. (Based on information provided in "Inertial Confinement Fusion.pdf" by M. Ragheb dated on Jan. 14, 2015.) Clearly, systems employing neutral species, like those described herein, have a strong advantage by virtue of their higher densities. The rate of fusion energy per unit volume for such systems exceeds that of tokamak and inertial confinement systems by at least about eight orders of magnitude. Thus, a system as disclosed herein can achieve a defined rate of energy production in about one-hundred-millionth of the volume of a tokamak or internal confinement system.

Coulombic Barrier Reduction

As explained, credible, prior approaches to nuclear fusion have energized fusion reactants and the supporting environment to extremely high temperatures, on the order of at least 150,000,000K (13000 eV). This is done to impart sufficient kinetic energy to the fusion reactants to overcome their natural electrostatic repulsion. In this environment, each reactant is a nucleus having an intrinsic positive charge which must first be overcome to allow some probability of a fusion reaction.

Certain embodiments of the present disclosure employ much lower temperatures; e.g., on the order of 2000K (0.17 eV) in fusion reactions. These embodiments employ neutral species as one or more reactants and/or modify the reaction environment to reduce the strong Coulombic repulsive force between reactant nuclei. Reduction of the Coulombic force may be accomplished in various ways including, for example, (i) providing an electron rich field in the region of the reaction and/or (ii) aligning the quantum mechanical spins of reactant nuclei. Depending on the structure of the reactor, the apparatus and methods for reducing Coulombic repulsion may take many forms. The following description assumes that the reactor includes an annular space with an outer confining wall or shroud. Other reactor structures can likewise produce reduced Coulombic repulsion environments that support fusion, but they may accomplish this in manners different than the one that follows.

The following is provided as one possible explanation of the environment near the inner surface of a confining electrode and should not be construed as a limitation on the practice of the disclosed embodiments. In this explanation, reactant species, particularly neutrals, rotate at high velocity and strike the inner surface of the electrode. Concurrently, electrons are emitted from or near the confining wall. The rapidly rotating neutrals have high angular velocity and therefore exert extreme pressure on the inner surface of the confining wall through an associated centrifugal force. Electrons emitted from the inner surface of the wall oppose this force.

The emitted electrons will diffuse away from the location where they are emitted, e.g., away from the wall and toward an interior space. However, the centrifugal force of the neutrals constrains the electrons to the region near the inner surface of the outer electrode. A resulting thin region of balanced forces adjacent to the inner surface of the electrode possesses a strong field that reduces the Coulombic repulsion between reactant nuclei.

The force balance may be expressed mathematically as the equilibrium of (i) the gradient (in a direction away from the wall surface in which electrons are emitted) of the product of the temperature and the density of electrons and neutrals, and (ii) the centrifugal force exerted toward the inner surface. The centrifugal force is proportional to the product of the neutrals' density, the radial position, and the square of their angular velocity.

$$\frac{\partial}{\partial r}(n_e K T_e + n_0 K T_0) = n_0 m_0 \omega^2 r$$

In this expression, r is the radial direction away from the inner surface of the confining electrode, K is the Boltzmann constant, T_e and T_0 are the electron and neutral temperatures in Kelvin, n_e and n_0 are the densities of electrons and neutrals, n_0 is the density of neutral species, m_0 is the mass of one rotating neutral species (e.g., a hydrogen atom), and ω^2 is the square of the angular velocity of the rotating neutral species.

In a thin region next to the surface from which the electrons are emitted (e.g., the inner surface of the confining wall), the free electrons create a strong electrical field (see the schematic representation of electron-rich region **232** adjacent confining wall **210** in FIG. **2***a-b*). The high concentration of neutrals limits the mean free path of the electrons, preventing them from following ballistic trajectories and thus obtaining sufficient kinetic energy to signifi-

cantly ionize the neutrals. Also, there are relatively few positive ions available for recombination because the neutrals have a significantly higher density than the ions. For example, the prevalence of ions to neutrals may be in the ranges of less than about 1:10, less than about 1:100, less than about 1:1000, or less than about 1:10000. Hence the neutrals are frequently positioned between the electrons and positive ions. This set of conditions produces a high concentration of excess electrons near the confining wall's inner surface and hence a strong electric field.

The combination of a large excess of electrons (over ions) in a very thin region (e.g., next to the inner surface of the electrode) and in the presence of a high concentration of neutrals produces a very strong electric field. In this region, the strong field reduces the Coulombic repulsion of interacting positively charged nuclei. Hence, the probability of two positively charged nuclei coming in close proximity is significantly increased.

Additionally, as mentioned, rotating particles impinging on the inner surface of the confining wall produce repeated opportunities for interacting fusion reactants. Neutrals repeatedly pass through the electron-rich layer and strike the inner surface of the confining wall or shroud and reenter the interior space of the reactor. This impingement on the wall represents the radial component of centrifugal force produced by particles rotating in a constrained environment (e.g., the inner surface of the confining wall). The repeated collisions, contact, or strikes increase the probability of a fusion reaction in a given area over a given period of time. The repetition replaces the need for a long confinement time and addresses the concerns that led to Lawson's criterion for characterizing prior approaches to fusion reactions. In simple terms, the overall probability of a fusion reaction is increased significantly.

As an example, the electron-rich region may be characterized by any combination of the following parameter values:

Density of free electrons: about $10^{23}/cm^3$

Density of neutrals: about $10^{20}/cm^3$

Density of positive ions: about 10^{15}-$10^{16}/cm^3$ (about 10^{-5} to 0.01% of neutrals)

Difference in densities of electrons and positive ions: about 10^6 to $10^8/cm^3$

Thickness (radial) of free electron-rich region (region where most of the electron density gradient exists): about 1 micrometer

Electric field strength in the electron-rich region: about 10^6 to 10^8 V/m

Electron temperature: about 1800-2000 K. (about 0.15 to 0.17 eV)

Centripetal acceleration: about 10^9 g's (where g is the acceleration due to gravity=9.8 ms^{-2})

The free electrons in such systems may be viewed as collectively catalyzing the fusion reaction of two nuclei. By analogy, one or more muons in association with protons and deuterons are sometimes described as catalyzing the fusion of hydrogen and deuterium atoms. Just as muons catalyze the fusion by allowing two fusing nuclei to get closer to one another, the free electrons in the vicinity of fusing nuclei catalyze fusion reactions described herein. Effectively, the electrons reduce the energy barrier that prevents the two reactants from coming close enough to react. This is very similar to the action of any catalyst in a chemical or physical context. Both muons and electrons increase the rate of reaction but do not actually participate in the reaction; they simply reduce the energy barrier required to bring the reactants in close enough proximity to react.

However, muon and electron catalysis have few other similarities. Muon catalyzed fusion is not commercially viable for various reasons. Notably, muons have a much greater mass than electrons and hence producing them is much more energetically expensive. Further, only relatively few of them can be produced at any instant in time, which means the breakeven requirement for fusion is not attainable. For the proton-boron-11 reaction, breakeven fusion may require approximately 10^{17} successful fusion interactions per cubic centimeter per second. Only a few nuclei in a large pool would be able to benefit from muon catalyzed fusion, nowhere near the level needed to support fusion.

In contrast, electrons can be easily produced, and in high density. For example, in accordance with the techniques disclosed herein, electrons can be generated at densities of approximately 10^{20} per cubic centimeter or greater. With such high densities, the electrons act collectively to produce a high electric field, which over a relatively large volume reduces the Coulombic barrier to interaction between approaching nuclei. Such a relatively large volume permits the needed interactions to breakeven, i.e. at least about 10^{17} successful fusion interactions per cubic centimeter per second.

Terminology

A "reactor" is an apparatus in which one or more reactants react to produce one or more products, often with an accompanying release of energy. The one or more reactants are provided in a reactor by continuous delivery, intermittent delivery, and/or a one-time delivery. They may be provided in the form of gasses, liquids, or solids. In some cases, a reactant is provided as a component of a reaction; for example, it may be included in a structure of the reactor such as a wall. Boron 11, lithium 6, carbon 12, and the like may be provided in a confining wall of a reactor. In some cases, a reactant is provided from an external source such as from a gas supply tank. In certain embodiments, the reactor is configured to promote a nuclear fusion reaction having a Q>1. A reactor may have components for removal of products and/or energy produced during the reaction. Product removal components may be ports, passages, getters, and the like. Energy removal components may be heat exchangers and the like for removing thermal energy, inductors and similar structures for directly removing electrical energy, etc. The reactor components may permit products and energy to be removed continuously or intermittently. In certain embodiments, a reactor has one or more confining walls that contain the reactants, and in some cases, provides a source of reactant, an electrical field, etc. As illustrated throughout this disclosure, reactors suitable for providing a sustained fusion reaction may have many different designs.

A "rotor" is a reactor or reactor component in which one or more reactant or product species (particles) rotates in a space. The space may be defined at least in part by a confining wall as described herein. In some cases, the rotation is induced by a magnetic force, an electrical force, and/or a combination of the two, as in the case of a Lorentz force. In certain embodiments, the rotation is induced by applying an electrical and/or magnetic force to electrically charged particles in a manner that causes them to rotate in a confinement region; the rotating charged particles collide with neutrals to cause the neutrals to likewise rotate in the confinement region, a phenomenon sometimes called ion-molecule coupling. Because the neutrals are not affected by the electrical and/or magnetic force, they would not rotate in the confinement region absent the interaction with the

charged particles. The confining wall or other outer structure of the rotor may have many closed shapes as described herein. In some embodiments, the outer structure has a generally or substantially circular or cylindrical shape. In such cases, the shape need not be geometrically exact, but may exhibit certain variations such as eccentricity around an axis of rotation, non-continuous curvature such as vertices, and the like.

In some cases, the confinement region of a rotor has an interior rod or other structure arranged concentrically with respect to the confining wall. In such cases, the rotor has an "annular space" where the particles rotate. When used herein, an "annular space" refers to a confinement region wherein the region is substantially ring-shaped. It should be understood that some rotors do not have an interior rod or other structure to define an annular space. In such cases, the confinement region of the rotor is simply a hollow structure. While an annular space may have a generally cylindrical shape, such a shape may exhibit certain variations such as eccentricity around an axis of rotation, non-continuous curvature such as vertices, and the like.

The "Lorentz force" is provided by a combination of electric and magnetic forces on a charge due to the resulting electromagnetic fields. The magnitude and direction of the force is given by the cross product of the electric and magnetic fields; hence the force is sometimes referred to as J×B. When the electric and magnetic fields have orthogonal directions, the force applied to a charged particle has a rotational direction that may be represented by the right-hand rule mnemonic.

In fusion reactions, participating reactants and products, which may include protons, alpha particles, and boron (^{11}B), are not necessarily present in complete purity. To the extent that any such reactant, product, or other component of a reaction is presented herein, such component is understood to be substantially present. In other words, the component need not be present at the level of 100% but may be present at a lower level, e.g., about 95% by mass or about 99% by mass.

An aneutronic reaction is conventionally understood to be a fusion reaction in which neutrons carry no more than 1% of the total released energy. As used herein, an aneutronic reaction or a substantially aneutronic reaction is one that meets this criterion. Examples of aneutronic reactions include:

$p+B^{11}\rightarrow 3He^4+8.68$ MeV

$D+He^3\rightarrow He^4+p+18.35$ MeV

$p+Li^6\rightarrow He^4+He^3+4.02$ MeV

$p+Li^7\rightarrow 2He^4+17.35$ MeV

$p+p\rightarrow D+e^++\nu+1.44$ MeV

$D+p\rightarrow He^3+\gamma+5.49$ MeV

$He^3+He^3\rightarrow He^4+2p+12.86$ MeV

$p+C^{12}\rightarrow N^{13}+\gamma+1.94$ MeV

$N^{13}\rightarrow C^{13}+e^++\nu+\gamma+2.22$ MeV

$p+C^{13}\rightarrow N^{14}+\gamma+7.55$ MeV

$p+N^{14}\rightarrow O^{15}+\gamma+7.29$ MeV

$O^{15}\rightarrow N^{15}+e^++\nu+\gamma+2.76$ MeV

$p+N^{15}\rightarrow C^{12}+He^4+4.97$ MeV

$C^{12}+C^{12}\rightarrow Na^{23}+p+2.24$ MeV

$C^{12}+C^{12}\rightarrow Na^{20}+He^4+4.62$ MeV

$C^{12}+C^{12}\rightarrow Mg^{24}+\gamma+13.93$ MeV

Examples of neutronic reactions include

$D+T\rightarrow He^4+n+17.59$ MeV

$D+D\rightarrow He^3+n+3.27$ MeV

$T+T\rightarrow He^4+2n+11.33$ MeV

The coulombic repulsion force is the electrostatic force experienced by two or more particles of the same charge. For two interacting particles, it is proportional to the reciprocal of the square of the separation distance (Coulomb's law). Thus, the repulsion becomes significantly stronger as charged particles approach one another. The repulsive force experienced by a charged particle in an electric field produced by multiple charged particles is given by the superposition of the contributions of all charged particles in the vicinity.

Lowering the coulombic barrier means that the commonly known and understood coulombic repulsion force typically calculated or experienced between two isolated particles is "lowered" or reduced by some calculable degree when the particles are in some proximity to a sufficient number of electrons or other charged particles to reduce the repulsive force that isolated particles would otherwise experience. As an example, the presence of excess electrons at a density of XX reduce the coulombic repulsive force between two positively charged YY particles in the domain of the electrons by ZZ %.

Lorentzian Rotor Embodiments

First Embodiment

FIGS. **1***a-c* depict a first embodiment of a reactor in which charged particles, charged species, or ions are rotated by the Lorentz force. FIG. **1***a* is a cross-section view of a reactor, while FIG. **1***b* provides an isometric cutout view of the same reactor along of section A-A from FIG. **1***a*. Unless stated otherwise, directionality using the r, Θ, and z coordinates pertains to a cylindrical coordinate system as shown in FIG. **1***b*. In the depicted embodiment, a Lorentzian driven rotor has outer wall **110**, which also serves as the outer electrode, and concentric inner electrode **120**, sometimes referred to as a discharge rod, that is separated from the outer electrode by annular space **140**. An electric field is formed across the annular space by applying an electric potential between the inner electrode **120** and the shroud **140**. When a sufficient electric potential is applied between the electrodes, a portion of the gas in the annular space is ionized, and a radial plasma current across the annular space is generated. In various embodiments, the inner electrode is held at a high positive potential while the shroud is grounded such that the electric field, and the flow of current, is substantially in the positive r-direction.

FIG. **1***c* depicts how the Lorentzian force is used to drive charged particles azimuthally within the confining wall **110**. In FIG. **1***c*, the discharge rod has been removed and the axis has translated in the z-direction to improve clarity. While not shown, a magnet such as a permanent magnet or a superconducting magnet is used to generate an applied magnetic field that is substantially parallel to the z-axis (substantially

axial direction) within the annular space. The magnetic field is substantially perpendicular to the direction of the electrical current causing the moving charged particles, charged species, and ions to experience a Lorentz force in the azimuthal (or Θ) direction. For example, consider the case in which the discharge rod has a positive potential vis-à-vis the outer electrode (e.g., the discharge rod has an applied positive potential while the outer electrode is grounded), thereby producing an electric field in the r-direction (**144**). In this configuration positively charged ions will move in the r-direction towards the outer electrode through the annular space **140**. If a magnetic field concurrently points in the z-direction (**146**), the ions will experience a Lorentz force in the −Θ direction, or clockwise direction as viewed from the perspective shown in FIGS. **1***b* and **1***c*. In some cases the electric field and magnetic field may be at an angle that differs from the perpendicular yet is not parallel, such that perpendicular components, to a lesser or greater extent, are present in sufficient strength to create a sufficiently strong azimuthal Lorentz force. This azimuthal force acts on charged particles, charged species, and ions, which in turn couple with neutrals such that neutrals in the annular space between the central discharge rod and outer electrode also are made to move at high rotational velocity. The lack of any moving mechanical parts means that there is little limitation to the speed at which rotation can occur, thus providing rotation rates of neutrals and charged particles that are in excess of, for example, 100,000 RPS.

Reverse Electrical Polarity Embodiment

FIGS. **5***a-d* depict another embodiment in which a reactor may utilize a Lorentzian force to drive ions and neutrals, through ion-neutral coupling, into rotation. Reactors configured for reverse electrical polarity differ from the reactors depicted in FIGS. **1***a-c* in that the electric field, and the flow of current (by convention in the direction of positive charge movement), is substantially in the negative r-direction. FIG. **5***a* is a cross-section view of a reactor, while FIG. **5***b* provides an isometric cutout view of the same reactor along of section A-A from FIG. **5***a*. A reverse electrical polarity rotor has outer electrode **510** and concentric inner electrode **520** that is separated from the outer electrode by annular space **540**, sometimes referred to herein as a confinement region. A radial electric field directed towards the inner electrode may be formed in the annular space by applying an electric potential to the inner electrode and/or the outer electrode. When a sufficient electric potential is applied between the electrodes, a portion of the gas in the annular space is ionized, and a radial plasma current across the annular space is generated.

FIG. **5***c* depicts how the Lorentzian force is used to drive charged particles azimuthally within the reactor. In FIG. **5***c*, the inner electrode has been removed from view, and the depicted axis has been translated in the z-direction to improve clarity. While not shown, a magnet such as a permanent magnet or a superconducting magnet is used to generate an applied magnetic field that is substantially parallel to the z-axis (i.e., in a substantially axial direction) within the annular space. The magnetic field is substantially perpendicular to the direction of the electrical current causing the moving charged particles, charged species, and ions to experience a Lorentz force in the azimuthal (or Θ) direction. For example, consider the case in which the inner electrode has an applied negative potential while the outer electrode is grounded (or held at a positive potential) producing an electric field in the negative r-direction (**544**). In this configuration, positively charged ions will move in the negative r-direction towards the inner electrode through the annular space **540**. If a magnetic field concurrently points in the z-direction (**546**), the ions will experience a Lorentz force in the +Θ direction or counterclockwise direction as viewed from the perspective shown in FIGS. **5***b* and **5***c*. In some cases, the electric field and magnetic field may be at an angle that differs from the perpendicular yet is not parallel, such that perpendicular components, to a lesser or greater extent, are present in sufficient strength to create a sufficiently strong azimuthal Lorentz force. This azimuthal force acts on charged particles, charged species, and ions, which in turn couple with neutrals such that neutrals in the annular space are also made to move at high rotational velocity. The lack of any moving mechanical parts means that there is little limitation to the speed at which rotation can occur, thus providing rotation rates of neutrals and charged particles that are in excess of, for example, 100,000 RPS.

Reverse Fields Embodiment

FIGS. **6***a-d* depict multiple views of another reactor embodiment that utilizes a Lorentzian force to drive ions and neutrals, through ion-neutral coupling, into rotation. The reactor of this embodiment operates using a reverse fields configuration. Reactors having this configuration differ from the reactors depicted in FIGS. **1***a-c* and FIGS. **5***a-d* in that the orientation of the electric field and the magnetic field within the confinement region are reversed. In this configuration, the magnetic field, instead of being substantially parallel to the z-axis, is directed radially in the positive or negative r-direction. Similarly, the electric field, rather than being directed radially, is substantially parallel to the z-axis. FIG. **6***a* is an isometric view of the reactor, FIG. **6***b* is a view of the reactor in the z-direction, FIG. **6***c* is an isometric section view of the reactor (corresponding to line A-A in FIG. **6***b*), and FIG. **6***d* provides a side view of the reactor. The depicted embodiment includes an inner ring magnet **626** and a concentric outer ring magnet **616** that also serves as the confining wall. The ring magnets have their poles oriented in the same direction, such that corresponding surfaces of the inner and outer ring magnets are the same. In this case, the exterior surface is a north pole **658**, and the interior surface is a south pole **659**. In some embodiments, there may be one or more additional layers of material on the interior surface of magnet **658** such that the confining surface material is different from the magnetic material. The region between concentric magnets forms the annular space **640** which is bound in the z-direction by electrodes on one end of the confinement region **660***a* and electrodes on the other end of the confinement region **660***b*. Generally, all the electrodes on either side of the confinement region (corresponding to electrodes **660***a* or to electrodes **660***b*) are given a similar electric potential. Unlike in the depicted hybrid reactor, electrodes **660***a* (or to electrodes **660***b*) may be a single contiguous electrode forming, for example, a ring or a disk shape. If electrodes **660***a* are grounded and electrodes on the other side of the annular space **660***b* are given a positive potential then an electric field is applied through the confinement region in the positive z-direction. If the magnetic field points in the r-direction (as depicted) the orthogonal electric and magnetic fields cause ions to rotate azimuthally in the Θ direction (see, e.g., FIG. **6***c*). Alternatively, if an electric field was pointed in the negative z-direction by

applying a positive potential to electrodes **660***a* while grounding electrodes **660***b*, ions would rotate in the −Θ direction.

Wave-Particle Embodiments

A second embodiment of a controlled fusion device is shown in FIGS. **7***a* and **7***b* in which ions rotate as a result of oscillating electrostatic fields. In this embodiment ions are accelerated azimuthally by electric fields produced from multiple discrete wall electrodes **714** located on, or forming, an outer ring, optionally in combination with interior electrodes **724** located on, or forming, an inner ring to generate localized, azimuthally-varying electric fields within an annular space **740**. In some cases, the wall electrodes collectively form the confining wall, and in some cases, the wall electrodes may be disposed on or within a portion of a confining wall or scaffold. The electric field advances azimuthally in a controlled sequence such that the electrostatic force applied to ions proceeds sequentially in a substantially azimuthal direction (in the Θ or −Θ direction). In this way, charged species are accelerated akin to a Maglev train that is propelled by oscillating magnetic fields along a train track. An oscillatory potential may be applied to the electrodes. The oscillations may vary in phase or other parameter from one electrode to the next to induce or maintain rotational movement of ions.

Ions present in the annular space experience an electrostatic force as a result of electric fields, and only a relatively small number or percentage of ions are needed to drive large numbers or percentages of neutrals through the principle of ion-neutral coupling. Ions used to drive the neutrals into rotation may be generated by any suitable mechanism such as inductive or capacitive coupling. In some embodiments, ions are generated when an RF charge sequence is applied to the wall and/or interior electrodes. In some embodiments the wall and/or interior electrodes may first undergo an initial charge sequence to ionize some of the neutral gas in the annular space and then transition to a different charge sequence that drives the rotation of ions. For example, a charge profile used to ionize a gas might simply involve grounding the confining wall electrodes **714** while applying a high potential to the interior electrodes **724**. In some embodiments, a gas that is already partially ionized may be introduced into the annular space **740**.

While FIGS. **7***a* and **7***b* depict two binary charge profiles that may be used to drive ion rotation in the annular space, many alternative charge sequences are possible. In some charge sequences, an electrode may be, for instance, held at a ground potential for a duration of time or may have a charge sequence that is asymmetrical (e.g., a positive potential is held for twice the duration of a negative potential).

In certain embodiments, this system does not require a magnetic field such as an axial static magnetic field. FIG. **7***a* depicts an example of this embodiment taken at a first point in time when the electrodes are provided with a first potential profile such that ions (e.g., a cloud or a grouping of ions) **704** experiences a force in the −Θ^ direction. FIG. **7***b* depicts the embodiment of FIG. **7***a* at a later point in time when the electrodes are provided with a different potential profile such that ions **704** continue to experience an azimuthal force in the −Θ direction.

Hybrid Embodiments

In certain embodiments a reactor includes features for producing both Lorentzian force and an oscillating electrostatic field to drive ions and neutrals, through ion-neutral coupling, into rotation. At any stage of operation, the reactor may use one or both of these mechanisms. FIGS. **6***a-f* depict an example reactor suitable for such operation. FIG. **6***a* is an isometric view of the reactor, FIG. **6***b* is a view of the reactor in the z-direction, FIG. **6***c* is an isometric section view of the reactor (corresponding to line A-A in FIG. **6***b*), FIG. **6***d* provides a side view of the reactor, and FIGS. **6***e* and **6***f* are section views (corresponding to line B-B in FIG. **6***d*) at different points in time. The depicted embodiment includes an inner ring magnet **626** and a concentric outer ring magnet **616** that also serves as the confining wall. The ring magnets have their poles oriented in the same direction, such that corresponding surfaces of the inner and outer ring magnets are the same. In this case, the exterior surface is a north pole **658**, and the interior surface is a south pole **659**. In some embodiments, there may be one or more additional layers of material on the interior surface of magnet **658** such that the confining surface material is different from the magnetic material. The region between concentric magnets forms the annular space **640** which is bound in the z-direction by one or more pairs of electrodes **660***a* and **660***b*. When electrode pairs **660***a* and **660***b* are given different potentials, an electric field substantially parallel to the z-direction is generated in the annular space, for example, by applying a positive potential to electrodes **660***a* while grounding electrodes **660***b*. When ions are generated in the annular space, the orthogonal electric and magnetic fields cause them to rotate azimuthally in the −Θ direction (see, e.g., FIG. **6***c*). If a positive potential were applied to electrodes **660***b* while electrodes **660***a* were grounded, ions would rotate in the Θ direction.

In some embodiments, as depicted in FIGS. **6***a-e*, a plurality of electrodes **660***a* and **660***b* are distributed radially along the annular space. In such cases, the reactor may be driven in a fashion similar to that of the reactor in FIGS. **7***a* and **7***b*. During operation, each electrode pair is driven with a substantially similar electric potential that differs from the potential of an adjacent electrode pair such that a localized electric field is generated in the Θ direction. As depicted in FIGS. **6***d* and **6***e*, the voltages applied to electrode pairs can be modulated in a controlled sequence so that the electrostatic force applied to ions presents a substantially continuous azimuthally (in the Θ or −Θ direction) varying component. In some configurations, a reactor may be configured to operate in a manner that initially drives ions and neutrals by a Lorentzian force and then transitions to driving ions and neutrals using the just described alternating electrostatic fields. **6**.

Reactor Types (Sizes)

In one aspect, reactors may be classified into groups by the power output they provide. In this manner reactors of the present disclosure are, for purposes of this discussion, divided into small, medium and large scale reactors. Small scale reactors are typically capable of generating between about 1-10 kW of power. In some embodiments, these reactors are used for personal applications such as powering automobiles or providing power to a household. The next classification is medium scale reactors which typically deliver between about 10 kW-50 MW of power. Medium scale reactors may be used for larger applications such as server farms, and large vehicles such as trains, and submarines. Large scale reactors are reactors that are designed to output between about 50 MW-10 GW of power and may be used for large operations such as powering portions of a power grid and/or industrial power plants. While these three general classifications provide practical categories to which

the present disclosure may relate, reactors disclosed herein are not tied to any of these categories.

The surface area (product of the perimeter and axial direction) of a shroud or confining wall typically limits the maximum power that may be generated by a reactor. A shroud having a large surface area supports fusion reactions over the large area of an interior surface (e.g., **122** in FIG. **1***a*). For small scale reactors, the radius of the interior surface of the shroud is typically about 1 centimeter to about 2 meters and the surface area of the interior surface is typically between about 5 cm^3 and 20 cm^3. For a medium scale reactor, the radius of the interior surface of the shroud is typically about 2 m to about 10 m and the surface area of the interior surface is typically between about 25 m^3 and 150 m^3. For a large scale reactor, the radius of the interior surface of the shroud is typically about 10 meters to about 50 meters and the surface area of the interior surface is typically between about 125 m^3 and 628 m^3. In some cases the radius of the interior surface may be on the order of kilometers, having a similar footprint to the Large Hadron Collider (LHC) run the CERN laboratory in Switzerland. Each of the above values assumes a single reactor that stands alone or is part of a contiguous stack of reactors (described below).

First Embodiment

FIGS. **1***a-c* depict the structure of a reactor having concentric electrodes that utilizes a Lorentzian rotor to drive charged particles and fusion reactants into rotation. This embodiment has an inner electrode **120**, an outer electrode **110**, and an annular space **140** between the two electrodes. During operation, an applied potential between these electrodes creates an electric field **144** that is substantially in the r-direction. While not shown, this embodiment also includes permanent magnets or an electromagnet (e.g., a superconducting magnet) that generates a magnetic field **146** in the z-direction between the inner and outer electrodes. As depicted in FIG. **1***c*, charged particles moving between the electrodes experience an azimuthally directed force, or a Lorentzian force, as a result of the radial electric field and the axial magnetic field.

As shown, the reactor depicted in FIG. **1***a* has a gap **142** that radially separates the outer surface of the inner electrode **112** and the interior surface of the outer electrode **122**. While the surface areas of the facing surfaces of the inner and outer electrodes may dictate the scale of a reactor, the radial gap may remain relatively constant across a wide range of applications. In some cases, the upper limit of a gap may be limited by the power available to ionize gas in the annular [illegible] and generate a plasma current, while the lower limit

electrode in the z-direction may be limited by the type and configuration of magnets used to create the magnetic field. For example, if permanent magnets are placed on either end of the annular space along the z-direction (as depicted in FIG. **11**), the outer electrode may be limited to about 5 or about 10 cm in the z-direction. If, however, the magnetic field is generated using multiple permanent ring magnets, as shown in FIGS. **16** and **17**, or an electromagnet or a superconducting magnet, as shown in FIG. **10**, the length of the outer electrode in the z-direction may be much longer. For example, the outer electrode may be between about 1 meter and about 10 meters. Generally, the outer electrode **110** is of a similar length to the inner electrode **120**, however, this need not always be the case. In some embodiments, the inner electrode may extend beyond the outer electrode in one or both directions. In some embodiments, the length of the outer electrode may exceed the length of the inner electrode such that the outer electrode extends beyond the inner electrode in one or both directions.

While FIGS. **1***a-b* depict one configuration in which a solid, circular inner electrode is used in conjunction with circular outer electrodes, there are many permutations of electrode shapes that may be used in this configuration. Several non-limiting examples of alternate embodiments will be apparent to those of skill in the art and are discussed with reference to FIGS. **8***a-b* and FIGS. **9***a-c*. While several illustrative examples are provided, one can easily understand how many additional electrode shapes are feasible.

As depicted in FIG. **8***a*, in some embodiments the inner electrode **820** may be a ring-like structure that is not solid all the way through. Providing a cavity or an open space within the inner electrode may be useful for heat dissipation, the use of internal magnets such shown in FIGS. **17***a-c*, or the use of other components within the reactor. In some cases, the radius of the inner and outer electrodes may vary along the z-direction of a reactor. For example, as shown in FIG. **8***a*, an inner electrode **820** may have a larger circumference at some locations along the z-direction, reducing the gap **842** at those locations. Conversely, a uniform inner electrode may be used with an outer electrode having an inner radius that changes or even fluctuates along the z-direction. In some instances, such as the embodiment depicted in FIG. **8***b*, both the radius of the inner electrode **820** and the radius on the inner surface of the outer electrode **810** vary in the z-direction such that the gap **842** is maintained along the z-direction of the reactor.

FIGS. **9***a-c* depict cross sections of reactors that have non-circular cross sections. As depicted, in some embodiments, the inner electrode **920**, and the outer electrode **910** [illegible]

about once a minute, or about once an hour. In many embodiments, gas valves may be sealed, so there is no fluid flow during operation of the reactor.

In some cases, a reactant gas is maintained at standard temperature and pressure before generating a plasma in the confinement region. In some cases, such as when a vacuum enclosure is used, a vacuum pump may be used to lower the pressure to less than about 1×10^{-2} Torr, and in some cases less than about 1×10^{-6} Torr prior to striking a plasma in the confinement region. In some cases, to increase the density of

may be on order of about 10^{10} cm^{-3} to about 10^{23} cm^{-3}, and in some cases, the density of electrons is on the order of about 10^{23} cm^{-3} within this region. In some embodiments, the density of neutrals in the electron-rich region may be about 10^{16} cm^{-3} to about 10^{18} cm^{-3}, and in some cases, the neutrals density within the confinement region is on the order of about 10^{20} cm^{-3}. Positive ions may be found at a much lower density than neutrals within the electron-rich region. In some cases, the density of positive ions is about 10^{15} cm^{-3} to about 10^{16} cm^{-3}. In some cases the ratio of

a deuteron, the coulombic barrier is reduced. Nuclear magnetic moments play a role in quantum tunneling. Specifically, when the magnetic moments of two nuclei are parallel, an attractive force between the two nuclei is created. As a result, the total potential barrier between two nuclei with parallel magnetic moments is lowered, and a tunneling event is more likely to occur. The reverse is true when two nuclei have antiparallel magnetic moments, the potential barrier is increased, and tunneling is less likely to occur. When the magnetic moment of a particular type of nucleus is positive, the nucleus tends to align its magnetic moment in the direction of an applied magnetic field. Conversely, when the moment is negative, the nucleus tends to align antiparallel to an applied field. Most nuclei, including most nuclei which are of interest as potential fusion reactants, have positive magnetic moments (p, D, T, ^{6}Li, ^{7}Li, and ^{11}B all have positive moments; ^{3}He and ^{15}N have negative moments). In certain embodiments, a magnetic field is provided that aligns the magnetic moments in approximately the same direction at every point within the device where a magnetic field is present. This results in a reduction of the total potential energy barrier between nuclei when the first and second working materials have nuclear magnetic moments which are either both positive or both negative. It is believed that this leads to an increased rate of tunneling and a greater occurrence of fusion reactions. This effect may also be referred to as spin polarization or magnetic dipole-dipole interaction. In addition, the gyration of a nucleus about a magnetic field line also contributes to determining the total angular momentum of the nucleus. So when the cyclotron motion of the nucleus produces additional angular momentum in the same direction as the polarization of the nuclear magnetic moment, the Coulomb barrier is further reduced.

In some cases, the spin states of fusion reactants (e.g., ^{1}H and ^{11}B) in the confinement region and along the confining wall may be aligned by applying a magnetic field in the range of 1-20 T. In cases in which a magnetic field is used to provide a Lorentzian force, the magnetic field may also align the spin states of the fusion reactants. The combination of a reduced coulombic barrier through, e.g., electron screening and a spin polarization (enabled by a strong magnetic field acting on the reactant nuclei) may produce a significant enhancement in the rate fusion. The electrostatic attraction between two nuclei includes a spin-dependent term that becomes dominate at short distances (e.g., less than 1 fm).

Applications

Fusion reactors as described herein have abundant applications that may resolve many societal issues such dependence on fossil fuels. In some cases, the use of fusion reactors may make feasible and/or practical energy intensive applications that were not feasible or practical with conventional power generation methods. A few applications of fusion reactors are now briefly discussed.

In some cases, fusion reactors may be used to retrofit a fossil fuel power plant such as a power plant which burns coal, natural gas, or petroleum to produce electricity. In some cases, fusion reactors described herein may be used to retrofit a fission power plant. When retrofitting a power plant, in some cases, it may only be necessary to replace or update the portions of the power plant where energy is produced. This makes power plant retrofits simple and cost efficient as turbines, generators, cooling towers, connections to a power distribution network, and other infrastructure may be reused. For example, a coal power plant may be retrofitted by replacing a coal-fired boiler with a fusion boiler that utilizes a reactor described herein. Similarly, a fission power plant may be retrofitted by replacing the control rods and uranium fuel with a fusion reactor as described herein.

In some cases, a fusion reactor has a modular design that employs a plurality of smaller reactors. By having a plurality of reactors, the power output of a plant may be modulated to meet energy demand by varying the number of reactors in operation. Additionally, if individual reactors can be serviced or replaced while other reactors remain operable, the overall power output of the plant may not be significantly affected.

In some cases, a fusion reactor may be used as a heating interface for industrial processes such as fiberglass manufacture. In some cases, a reactor is configured as the heat source for a steam generator (e.g., a steam generator used for steam cleaning or metal cutting). In some cases, a reactor is used as a source of helium where helium is produced as a result of a fusion reaction (e.g., when the reactor conducts proton-boron-11 fusion). In some cases, the reactor may be used as part of a water heater, such as a home-sized water heater. For example, the reactor may be placed within a water tank or may be thermally coupled to a water tank such that heat emanating from the reactor is used to heat water. In some cases, a fusion-based water heater may be paired with a water radiator to provide indoor heating.

In some cases, a fusion reactor is used for transportation applications. For example, a fusion reactor may be used to power and automobiles, planes, trains, and boats. An automobile, for instance, may be outfitted with a reactor having one or more energy conversion modules configured to generate electrical and/or mechanical energy. In an electric car, electrical energy produced by a reactor may be used to charge a battery or capacitor which is used to provide power to an electric motor. For example, a reactor may be operated to charge a car battery whenever the battery's state of charge falls below a certain threshold value. In some cases, mechanical energy is produced by, for example, a Stirling engine which is used to provide the driving power for a car. In some cases, a fusion reactor may be used to provide power to outer space vehicles. Some designs for outer space vehicles use a fission reactor such as a radioisotope thermoelectric generator. Such designs suffer from use and generation radioactive isotopes. They also require carrying relatively large amounts of radioactive fuel. Since reactors described herein may be aneutronic or substantially aneutronic, these reactors may be much more preferable for spacecraft designed to carry human occupants. Additionally, the energy densities of fusion reactants used for reactors described herein are significantly higher than fuels required by a fission reaction or a chemical reaction to produce the same amount of energy.

The claim elements that do not recite "means" or "step" are not in "means plus function" or "step plus function" form. (See, 35 USC § 112(f)). Applicant's intend that only claim elements reciting "means" or "step" be interpreted under or in accordance with 35 U.S.C. § 112(f).

The present disclosure may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the disclosure is, therefore, indicated by the appended claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

What is claimed is:

1. An apparatus comprising:

a first electrode having a substantially cylindrical inner surface that has a longitudinal axis and forms at least a portion of a confining wall, wherein the confining wall at least partially encloses a confinement region;

a second electrode located within a region interior to the first electrode and separated from the first electrode by at least the confinement region;

at least one magnet configured to provide a magnetic field through the confinement region, at least a portion of the magnetic field in the confinement region being substantially parallel to the longitudinal axis;

an inlet to the confinement region for permitting introduction of a fluid to the confinement region, the fluid containing a first reactant;

a second reactant; and

a control system comprising one or both of a voltage source and a current source and configured to (a) control a potential of an electric field substantially orthogonal to the longitudinal axis, the potential between the first electrode and the second electrode being sufficient to produce an electrical current from the first electrode to the second electrode; (b) generate, from the first reactant, a weakly ionized plasma of ions and neutrals; and (c) by interaction of the electric field and the magnetic field, produce a Lorentzian force that induces azimuthal rotation of the ions around the longitudinal axis, the azimuthal rotation of the ions imparting azimuthal rotation to neutrals of the first reactant, and promoting repeated collisions between one or both of the ions and the neutrals with the second reactant; wherein, during operation:

the repeated collisions between the neutral particles and the reactant produce an interaction produces a product having a nuclear mass that is different from a nuclear mass of any of the nuclei of the neutrals and the second reactant and,

a mole fraction of the ions to the neutrals in the weakly ionized plasma is in the range about of 0.0001% to about 1%.

2. The apparatus of claim 1, wherein the second electrode has a diameter of at most about 0.5 inches.

3. The apparatus of claim 1, wherein the second electrode has a length in a direction parallel to the longitudinal axis.

4. The apparatus of claim 1, further comprising a ceramic block thermally coupled to the second electrode and configured to remove thermal energy from the second electrode via conduction.

5. The apparatus of claim 1, further comprising a linear actuator that is configured to move the second electrode in a direction that is substantially parallel to the longitudinal axis.

6. The apparatus of claim 1, wherein the first electrode and the second electrode are separated by a gap of between about 0.1 mm and about 20 cm.

7. The apparatus of claim 1, wherein the at least one magnet comprises at least one permanent magnet having opposite magnetic poles offset from one another in the direction of the longitudinal axis.

8. The apparatus of claim 1, wherein the at least one magnet comprises two permanent magnets separated from one another by at least the confinement region and in the direction of the longitudinal axis.

9. The apparatus of claim 1, wherein the second electrode is coated with an electron emitting material.

10. The apparatus of claim 1, wherein the reactant comprises boron 11.

11. The apparatus of claim 1, wherein the confining wall comprises one or both of a refractory metal and a stainless steel.

12. The apparatus of claim 1, wherein the interaction is a fusion reaction.

13. The apparatus of claim 1, wherein the interaction is an aneutronic fusion reaction.

14. The apparatus of claim 1, wherein the neutral particles comprise one or more of neutral hydrogen, deuterium, and tritium.

15. The apparatus of claim 1, wherein, during operation, the neutral particles in the confinement region proximate the second electrode have a concentration of at least about $10^{20}/cm^3$.

16. The apparatus of claim 1, further comprising one or more electron emitters configured to, during operation, emit electrons into an electron-rich region adjacent to the second electrode.

17. The apparatus of claim 1, wherein the confinement region proximate the second electrode comprises an electron-rich region having at least about $10^6/cm^3$ more electrons than positively charged particles.

18. The apparatus of claim 16 wherein, during operation, the electron-rich region includes an electric field strength of at least about 10^6 V/m.

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